STATE OF CALIFORNIA

# DEPARTMENT OF TRANSPORTATION
## ENGINEERING SERVICE CENTER
### OFFICE OF MATERIALS ENGINEERING AND TESTING SERVICES

# DEVELOPMENT OF A PHYSICAL PROPERTY SPECIFICATION FOR ASPHALT-RUBBER BINDER

**FINAL REPORT # FHWA/CA/TL-94/07**
**CALTRANS STUDY # F93TL14**

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16. Abstract

The performance of projects incorporating asphalt-rubber binders has been inconsistent. Thus, a method was needed to provide an understanding of binder physical properties associated with the desirable performance and to quantify them for specification purposes. It was proposed to use the capabilities of a dynamic shear rheometer for comparing the asphalt-rubber binder properties with project performance data to determine the potential for rheological specifications on job samples of the binder.

Representative binders from six dense-graded and gap-graded hot mix projects were analyzed.

The conclusions were that the physical properties of an asphalt-rubber binder can be characterized using a dynamic shear rheometer and that the properties studied are related to performance at low, medium, and high temperatures to the extent of binder contribution to pavement performance. Rheological specifications are proposed for use on a trial basis.

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# INTRODUCTION

In the late 60's and early 70's, the blending of ground tire rubber and paving asphalt yielded patented binders which were reported to improve performance relative to standard paving asphalts.

Beginning in the mid 70's, the California Department of Transportation (Caltrans) began the trial use of these blended materials, referred to as asphalt-rubber binders in this report, to evaluate these claims. The initial uses were in chip seals or so called stress absorbing membranes (SAM) and in stress absorbing membrane interlayers (SAMI) where the chip seal is covered with a layer of asphalt concrete pavement. Caltrans experience with asphalt-rubber binders in SAMI applications has led to its non-experimental use in overlays of distressed asphalt concrete pavements. The specifications used for the asphalt-rubber binders were recipes recommended by the manufacturers. Because these binders are non-homogeneous, they confound characterization by typical paving asphalt specification tests such as penetration (AASHTO T-49) and absolute viscosity (AASHTO T-202).

Subsequent use of these binders has also been in dense-graded asphalt concrete and recently in gap-graded asphalt concrete. Caltrans designation for these types of pavements has been established as asphalt-rubber hot mix-dense graded (ARHM-DG) and asphalt-rubber hot mix-gap graded (ARHM-GG).

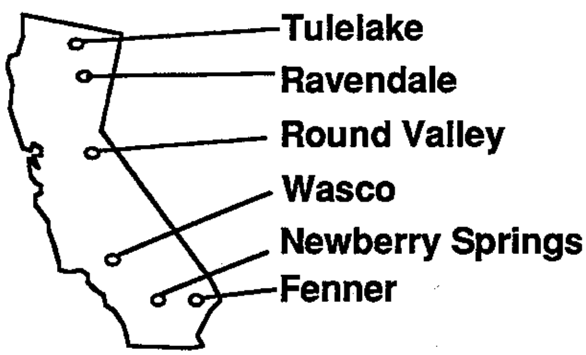
The performance of the projects incorporating these binders has been inconsistent (1). In asphalt-rubber dense-graded and gap-graded overlay projects, the time at which the reflection of thermal and/or fatigue cracking has been observed has ranged from less than one year to nine years. Thus, it appeared that a method was needed to provide an understanding of the physical properties that were contributing to the desirable performance and to quantify these properties for specification purposes. Similarly driven processes have resulted in specifications for standard paving asphalts and modified asphalts that are based on need to prevent premature fatigue cracking, rutting, and thermal cracking, and the effect of climate and aging on each. It should be kept in mind that binder properties can only be relied on for pavement performance to the extent that they contribute to this performance. Aggregate properties, mix formulations, and construction practices are also very important and frequently override binder properties.

Through the use of a dynamic shear rheometer (DSR), an understanding of the beneficial visco-elastic properties of binders is developing via a comparison with performance data. Thus, it was proposed to use the analytical capabilities of the DSR for comparing the asphalt-rubber binder properties with project performance data to determine if a specification could be developed for this binder. A Rheometrics RAA was obtained with funding from the California Integrated Waste Management Board and an FHWA Type-B research project was developed for conducting the research. The RAA was selected because the sample geometry of the combined melts and solids (CMS) fixture facilitates the testing of non-homogeneous asphalt-rubber binders. A discussion of asphalt rheology and the principles of dynamic mechanical analysis is presented in Appendix A.

## APPROACH

Rheological analysis of standard paving asphalts and modified asphalts relative to pavement performance data has yielded parameters that are suitable for specification purposes for key performance criteria (2, 3). Climatic factors reflected in testing temperature and accelerated aging conditions are contained in the performance based asphalt (PBA) grading system (4) and the Strategic Highway Research Program (SHRP) asphalt specification (5). Thus, the approach chosen was to use these parameters and conditions to characterize the asphalt-rubber binders from ARHM-DG and ARHM-GG projects placed by Caltrans, then to compare these properties with performance data to determine the potential of rheological specifications for asphalt-rubber binders for hot mix. Project information and locations are shown below.

| Project | Year Placed | Location | Contract Number |
|---|---|---|---|
| Ravendale | 1983 | 02-LAS-395-92.0/101.4 | 02-189504 |
| Fenner | 1987 | 08-SBd-40-80.4/140.0 | 08-006714 |
| Tulelake | 1991 | 02-MOD-139-41.1/50.7 | 02-251804 |
| Round Valley | 1991 | 09-INY-395-125.3/127.7 | 09-251504 |
| Newberry Springs | 1992 | 08-SBd-40-15.0/31.0 | 08-305104 |
| Wasco | 1992 | 06-KER-46-49.8/50.9 | 06-312104 |



The binder analysis was based on testing job samples only, testing lab blends from project recipes only, and testing both job samples and lab blends. Supporting studies of formulation variables were also conducted.

The analysis of the hot mix projects will be presented by performance criteria with an introduction in each section to show the correlation of the measurement technique with performance data from projects using standard paving asphalts and polymer modified asphalts.

## PERFORMANCE PROPERTIES ANALYSIS

### Fatigue Cracking

A binder property that has been correlated with fatigue cracking is the shear susceptibility at 25° C (2). There are two shear susceptibility parameters. The shear susceptibility of viscosity (SSV) is calculated as:

$$SSV = \frac{\log \eta \text{ (10 rad / sec)} - \log \eta \text{ (1 rad / sec)}}{\log \text{ 10 rad / sec} - \log \text{ 1 rad / sec}}$$

The shear susceptibility of the phase angle delta (SSD) is calculated as:

$$SSD = \frac{\delta \text{ (10 rad/sec)} - \delta \text{ (1 rad/sec)}}{\log \text{ 10 rad/sec} - \log \text{ 1 rad/sec}}$$

The format for using these two parameters to understand a binders contribution to fatigue life is presented in Figure 1. The grid lines were established in the analysis of standard and modified binders in conjunction with beam fatigue life studies and the fatigue life of pavement test sections. The negatively sloped straight line is suggested as a line of risk for fatigue cracking based on the field data. Initial binder properties start on the right

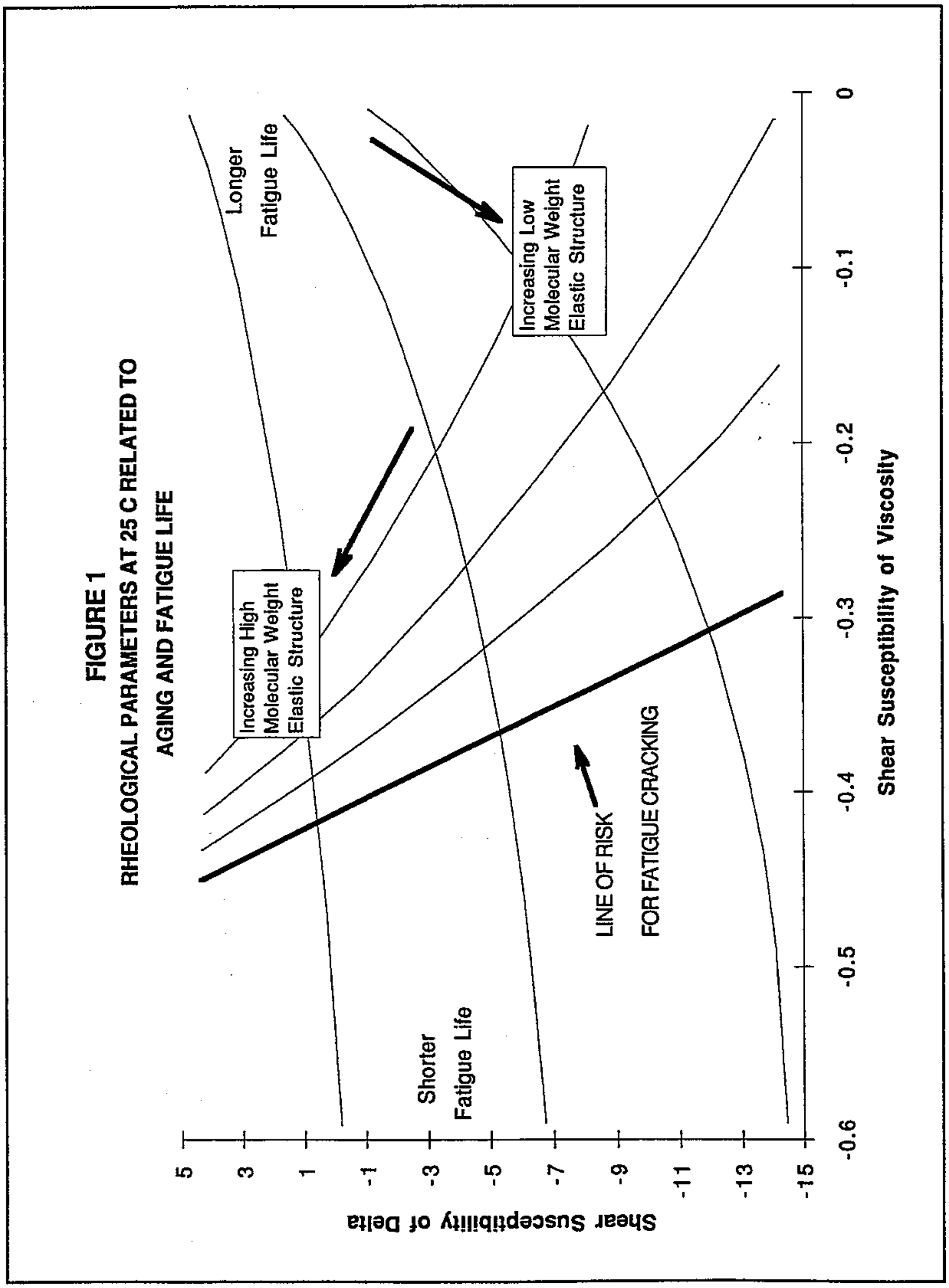
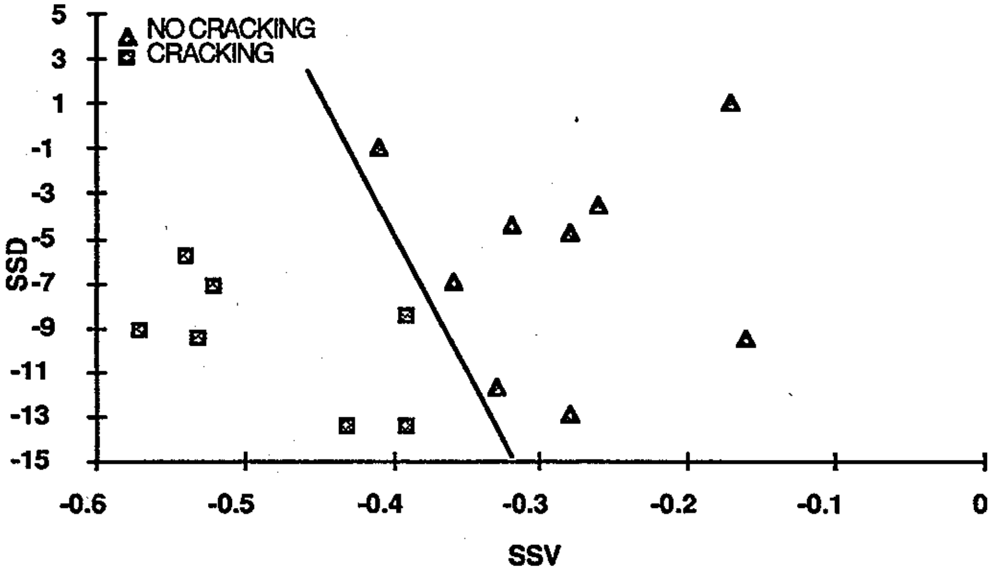



**FIGURE 1**
**RHEOLOGICAL PARAMETERS AT 25 C RELATED TO AGING AND FATIGUE LIFE**

side of the line and shift to the left in some manner due to aging. Standard asphalts and polymer modified binders from pavements that exhibit fatigue cracking (2) have had shear susceptibility parameters which placed them on the left side of the line as shown in the figure below.

**Data Related to Aging and Fatigue Cracking**




Thus, in the interest of fatigue, one should only need to determine the parameters SSD and SSV on a laboratory sample aged to approximate the climatic effect over the design life and see if these values stay to the right of the line of risk. This evaluation was done for the six projects even though some of the newer projects haven't been in place long enough to have experienced such aging. These parameters were also helpful in understanding the independent contributions of base asphalt and high molecular weight polymer to fatigue life (2). Since asphalt-rubber binders may contain up to four ingredients, the shear susceptibility parameters were determined on various combinations of ingredients and aging conditions.

**Ravendale**

Several test sections using ground tire rubber were constructed in 1983 on Route 395 near Ravendale (6). No samples of the blended asphalt-rubber binder (ARB) used during construction were available. However, a sample of the blended ground rubber was available. Project records indicate the formula of the asphalt-rubber binder was:

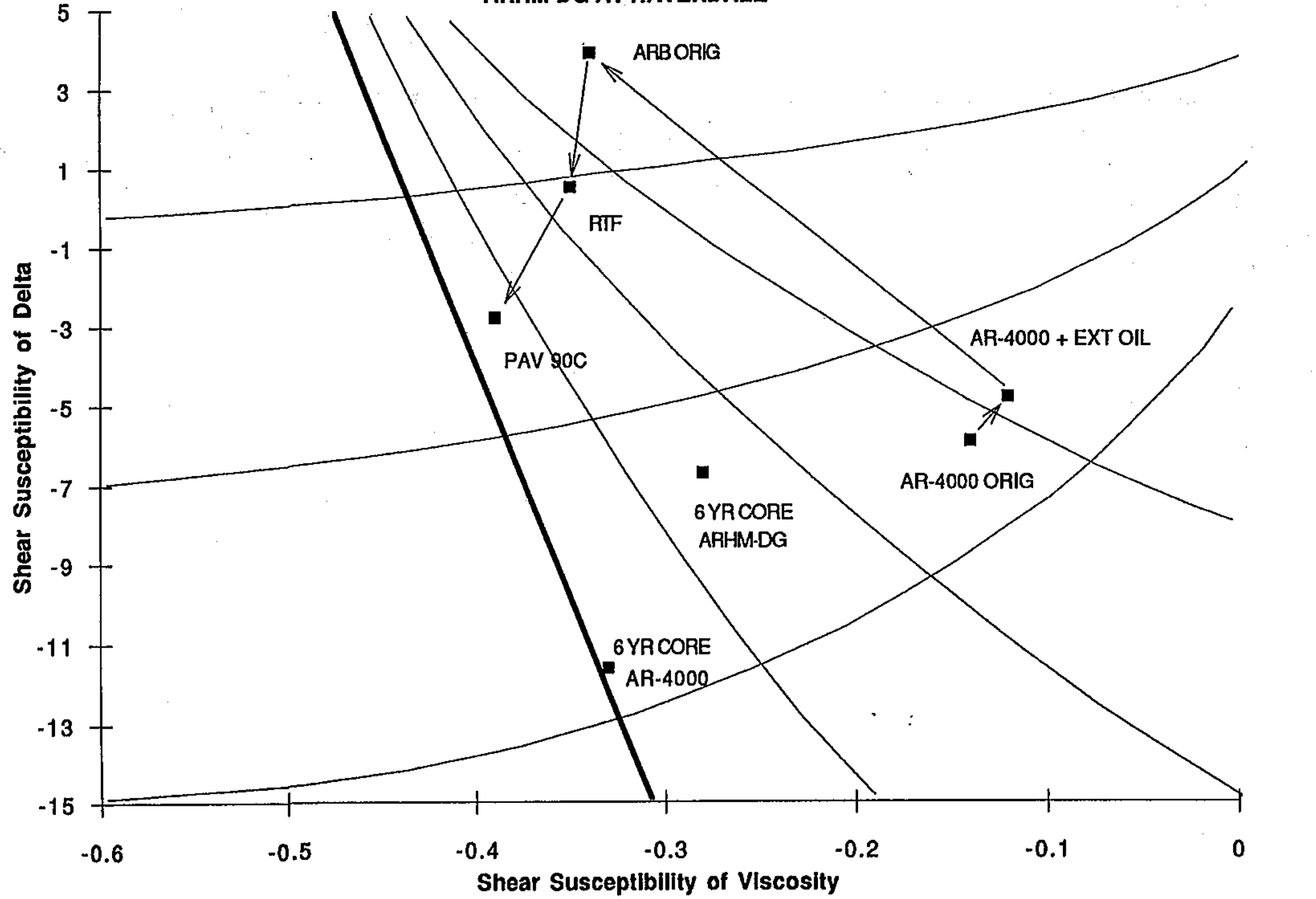
| | |
|---|---|
| 78% | Huntway AR-4000 |
| 18% | Ground tire rubber (80% Genstar G-274 and 20% Ramflex [devulcanized]) |
| 4% | Extender oil (Califlux GP) |

This blend was reacted for 45 minutes at 177° C (350° F)

An AR-4000 from Huntway that had the same properties as those indicated by the project quality control records was located. A sample of Califlux GP was provided by Witco Chemical. The ingredients were combined per the job formula and reacted for 45 minutes at 177° C. Portions of this blend were aged in the Rolling Thin Film Oven (AASHTO T-240) and then the Pressure Aging Vessel for 20 hours at 90° C (AASHTO PP-1). The shear susceptibility parameters were determined at 25° C for these materials, as well as the original AR-4000, a blend of the original AR-4000 (78 grams) and the extender oil (4 grams), binder recovered (California Test 380) from a six-year core of ARHM-DG, and binder recovered from a 6-year core of the control (conventional dense-graded AC containing AR-4000). These data points are plotted in Figure 2.

Figure 2

ARHM-DG AT RAVENDALE



There are several observations and questions that arise from this data:

1) The 90° C conditioning used for the ARB is consistent with the aging experienced by the control AR-4000 in six years (i.e., both have moved just to the right of the "line of risk").

2) The binder recovered from the six year ARHM-DG core appears to have experienced less aging than the control AR-4000.

3) The recovery process removed the majority of the high molecular weight elastic structure from the ARB.

4) The shift due to aging is similar to that observed for polymer modified asphalts, both field and laboratory aged (2).

5) As high molecular weight elastic structure was added to the base asphalt and extender oil, the appropriate "vertical" response is observed, but also observed is a "horizontal" shift. This could mean that the contour lines are different for ARB or that during the reaction process some of the extender oil contained in the ground rubber (7) is diffusing into the base asphalt.

To explore these possibilities, a sample of the ground tire rubber from the project was subjected to the routine asphalt recovery process using tricholoroethylene (TCE) to remove any extender oil in the rubber. Rough quantitative analysis indicated about 15 percent of the rubber mass was removed in this process. The ground tire rubber was then dried of solvent and used in making a job formula ARB. A portion of this blend was aged in the PAV @ 90° C. The shear susceptibility parameters were determined for the original blend using the "dry" rubber and the PAV residue. These data points are plotted in Figure 3.

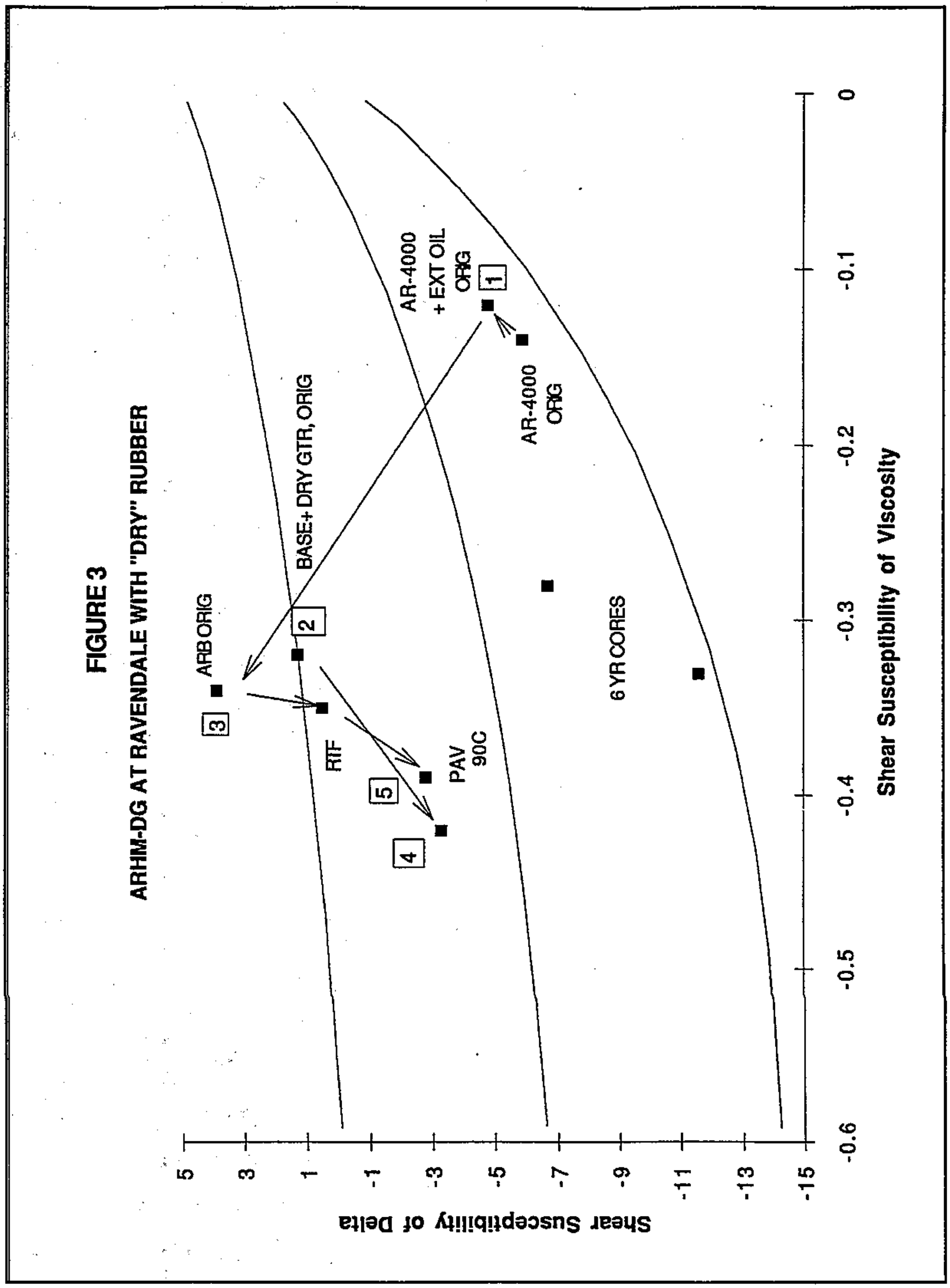


FIGURE 3
ARHM-DG AT RAVENDALE WITH "DRY" RUBBER
Shear Susceptibility of Delta
Shear Susceptibility of Viscosity
5
3
1
-1
-3
-5
-7
-9
-11
-13
-15
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
AR-4000
+ EXT OIL
ORIG
1
AR-4000
ORIG
BASE+ DRY GTR, ORIG
2
ARB ORIG
3
RTF
5
4
PAV
90C
6 YR CORES

The following observations are made:

1) The difference in "horizontal" shift within the "vertical" grid lines (compare DP-1 to DP-2) indicates that there is some diffusion of rubber based extender oil into the asphalt during the reaction process.

   Note: In the data point identification system used in several of the figures, only the numeral is used.

2) The "vertical" shift indicates that the grid lines are appropriate.

3) The drying process appears to have been severe enough to effect the properties of the rubber (compare DP-2 vs. DP-3). The drying was accomplished in a 150° C forced draft oven for about 2 hours.

4) The lack of rubber-based extender oil was detrimental to the fatigue properties with age (DP-4 vs. DP-5). Note that the PAV residue of DP-4 has shifted across the line of risk for fatigue cracking.

The observation of oil extraction from the ground rubber in the solvent recovery process raises a question regarding the appropriateness of recovering ARB from field cores to analyze binder properties. To pursue this, the residue from the PAV conditioning at 90° C of the job blend (DP-5) was subjected to a mini-recovery process using TCE, rubber screening with a filter paper on a 400 mesh sieve, and thin film drying at about 120° C. The shear susceptibility parameters of this residue (DP-6) are plotted in Figure 4.

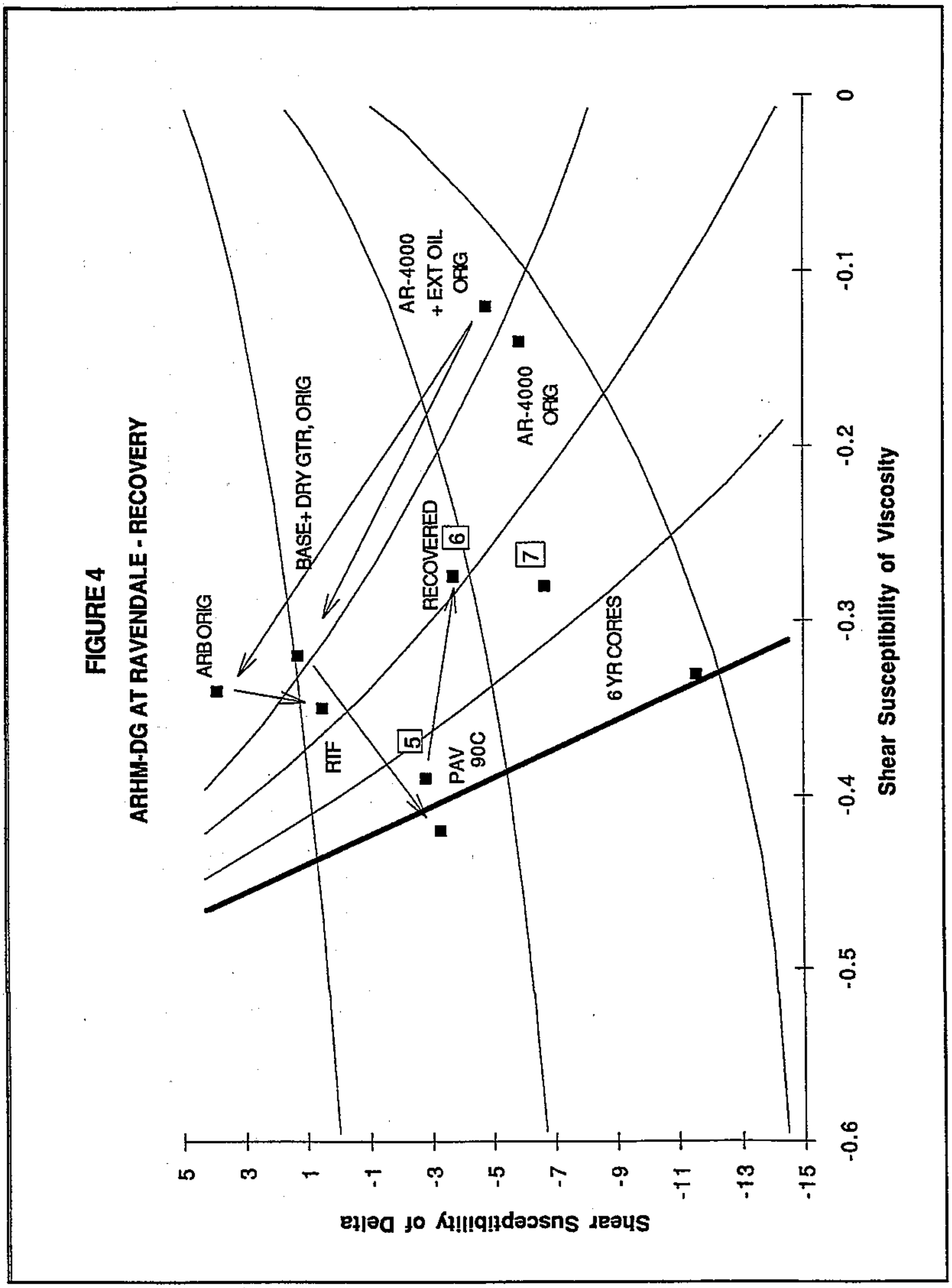


FIGURE 4
ARHM-DG AT RAVENDALE - RECOVERY
ARB ORIG
BASE+ DRY GTR, ORIG
AR-4000
+ EXT OIL
ORIG
AR-4000
ORIG
RECOVERED
6
7
5
RTF
PAV
90C
6 YR CORES
Shear Susceptibility of Delta
Shear Susceptibility of Viscosity
5
3
1
-1
-3
-5
-7
-9
-11
-13
-15
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0

The following observations are made:

1) The separation of high molecular weight elastic structure is noticeably less efficient when the centrifuge step is left out of the recovery process. Compare the "vertical" component of DP-6 to DP-7.

2) Even after a significant aging period, the state of the extender oil still in the ground rubber and the removal efficiency of the solvent recovery process will lead to artificially softened properties if ARB is recovered using TCE. It is suspected that other solvents for asphalt would yield the same results.

Therefore, it appears that the data point (DP-5) indicated for the PAV residue at 90° C for the Ravendale ARB is a more appropriate characterization of the shear susceptibility of the binder after six years than that plotted for the binder recovered from the core (DP-7).

The performance data from these sections indicated that both the 150 mm control section and the 75 mm ARHM-DG/SAMI section were just beginning to show fatigue cracking after six years.

**Fenner**

Two half-mile test sections of ARHM-DG were placed within an overlay project in the desert on Interstate 40 in 1987. The project DGAC with AR-4000 was placed 90 mm thick. The ARHM-DG sections were placed in thicknesses of 60 mm and 90 mm. Neither included a SAMI. There was a job sample of the ARB available, but none of the original ingredients. The formulation was reported as Edgington AR-4000 (84%) and Altos 1710 (16%). A sample of Edgington AR-4000 from 1988 was available and Altos supplied a sample of their 1710 ground tire rubber. These were blended for 45 minutes at 177° C.

Both the job sample and the lab blend of ARB were aged in the PAV at 110° C to approximate in-service aging. Another portion of the job sample was also aged in the Tilt Oven for 3 days at 113° C to approximate in-service aging using this equivalent procedure (2). The shear susceptibility parameters were determined for the base asphalt and the original and aged residues of both ARBs. These data are plotted in Figure 5.

The following observations are made:

1) The job sample (DP-1) appears to contain more than 16 percent rubber (DP-2). Compare the vertical component of the DP-1 to DP-2.

2) A "horizontal" shift due to rubber-based extender oil diffusion is seen in both blends, but to a lesser degree in the lab blend.

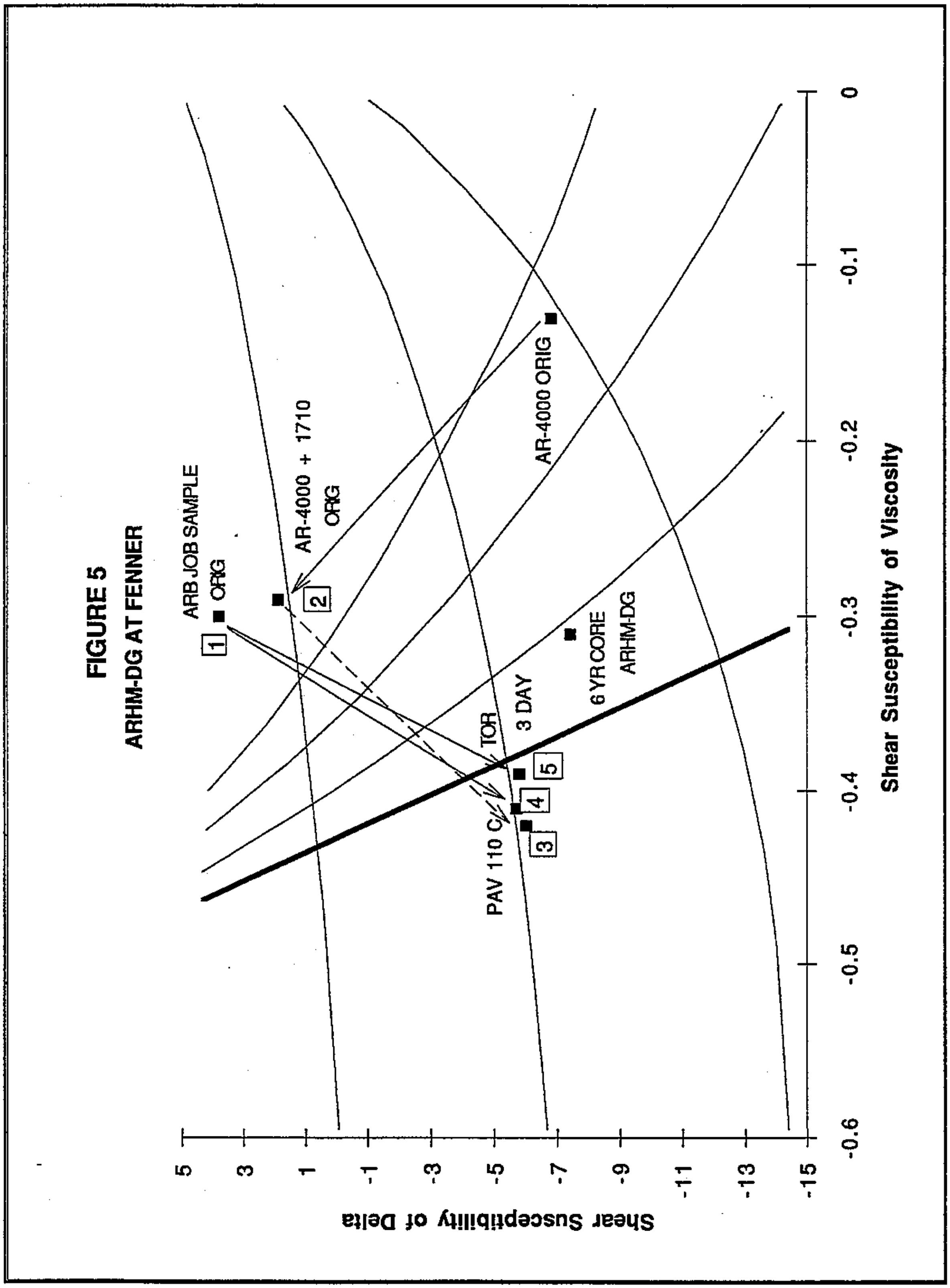
3) The shift due to aging is similar but the lab blend (DP-3), with what appears to be a lesser amount of rubber-based extender oil, aged more; i.e., DP-3 is to the left of DP-4 and DP-5.

4) All of the aged residues are to the left of the line of risk for fatigue cracking.

5) The PAV conditioning at 110° C for 20 hours (DP-4) and the Tilt-Oven exposure at 113° C for 3 days (DP-5) yielded residues aged to the same degree for rheological characterization.

6) The binder recovered from the six-year core of ARHM-DG appears to have aged less than expected per the PAV simulation for the desert climate.

**FIGURE 5**
**ARHM-DG AT FENNER**



Similar to the component evaluations performed on the Ravendale project, additional evaluations were conducted on the components on the Fenner project. The ground rubber was subjected to TCE and the rubber-based extender oil was recovered. In this case, the rubber was dried for a few days under a hood and then for about 1 hour at 113° C. A blend was made containing 16 percent of the "dry" rubber, and a portion of this was conditioned in the PAV at 110° C. The TCE was distilled off of the rubber-based extender oil and a blend was made containing 3 percent of this oil and 97 percent AR-4000. A portion of this blend and the neat AR-4000 were aged in the PAV at 110° C. Also, this lab blend of the ARB that had been aged in the PAV was subjected to an inefficient solvent recovery process to simulate the binder recovered from a field core. The term "inefficient" is used here because after each 10-15 minute exposure to fresh TCE, the freed rubber was decanted along with the solution onto the filter paper. (The decanting step should have included a screen so that all of the ground rubber was exposed to each solvent dissolution period.) As before, the recovered binder was dried in thin films at about 120° C. The shear susceptibility parameters were determined for the binders above. The data are plotted in Figure 6 with the following observations:

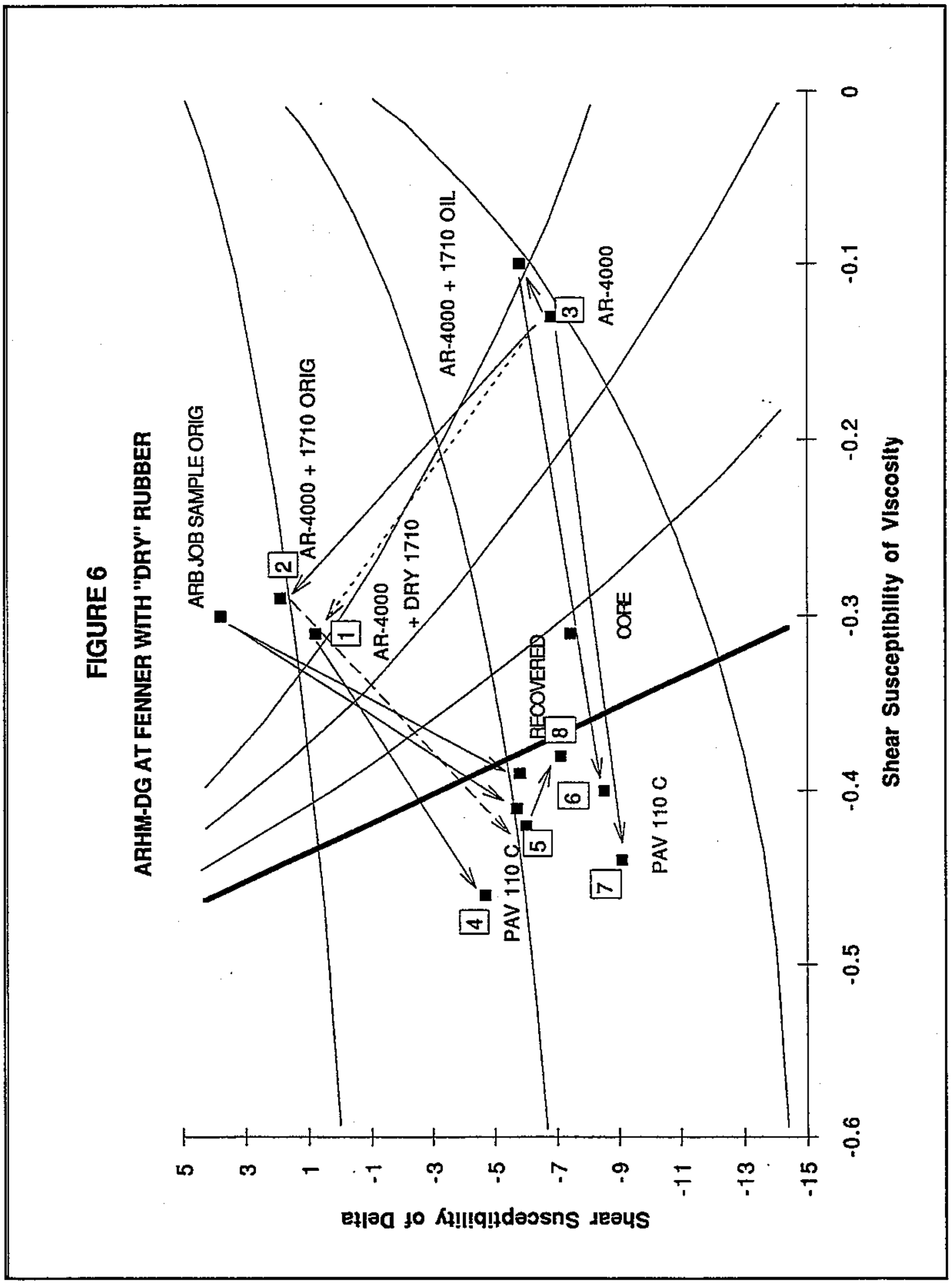



FIGURE 6

ARHM-DG AT FENNER WITH "DRY" RUBBER

1) The original property of the ARB using the "dry" 1710 (DP-1) supports the hypothesis of diffusion of rubber-based extender oil during reaction (compare the horizontal proximity of DP-1 to DP-2). The ground rubber apparently still contained some rubber-based extender oil as indicated by the horizontal component of DP-1 in comparison with that of DP-3.

2) The amount of rubber-based extender oil that had been removed from the ground rubber is apparent in the PAV aged residue in the concomitant shift to the left. Compare the horizontal components of DP-4 and DP-5.

3) The hypothesis of rubber-based extender oil diffusion into the asphalt during reaction is further supported by the comparison of the distance to left of the line of risk for the pair of <u>PAV</u> residues of the AR-4000 containing 3 percent rubber-based extender oil (DP-6) and the lab blended ARB (DP-5), with the two "dry" <u>PAV</u> residues of the neat AR-4000 (DP-7) and the ARB using the "dry" ground tire rubber (DP-4).

   The binders with the greater amount of rubber-based extender oil, whether added directly to the AR-4000 or diffused into the AR-4000 from the rubber, are farther to the right than those without.

4) The properties of the binder recovered (DP-8) from the PAV residue of the ARB also indicate the inappropriateness of recovering binder from pavement cores containing ground tire rubber.

In terms of field performance, the 60 mm ARHM-DG exhibited fatigue cracking after one year as well as the control AR-4000 at 90 mm. This suggests that the structural section was under designed. The 90 mm ARHM-DG exhibited fatigue cracking at about four years of age, which would be consistent with the properties of the residue from the PAV.

**Tulelake**

In 1991, a project was constructed on Route 139 in Modoc County. This location has a similar climate to Ravendale and shares another similarity in that several sections were placed with varying materials and structural sections. However, the pavement surface deflections prior to and after construction were considerably higher than those measured at Ravendale. From this project, samples were available of the job ARB and the ingredients. Thus, a blend was made containing 83 percent Witco PBA-2 and 17 percent Atlos 1900. Samples of these two binders were aged under various conditions and the shear susceptibility parameters determined. The data are plotted in Figure 7 with the following observations:

1) The original properties of the job sample and the lab blend compare favorably.

2) The Tilt-Oven Residue (TOR) after 18 hours at 113° C (with an RTF preconditioning) agrees favorably with the PAV residue at 90° C.

3) This binder should have good fatigue life even in a desert climate.

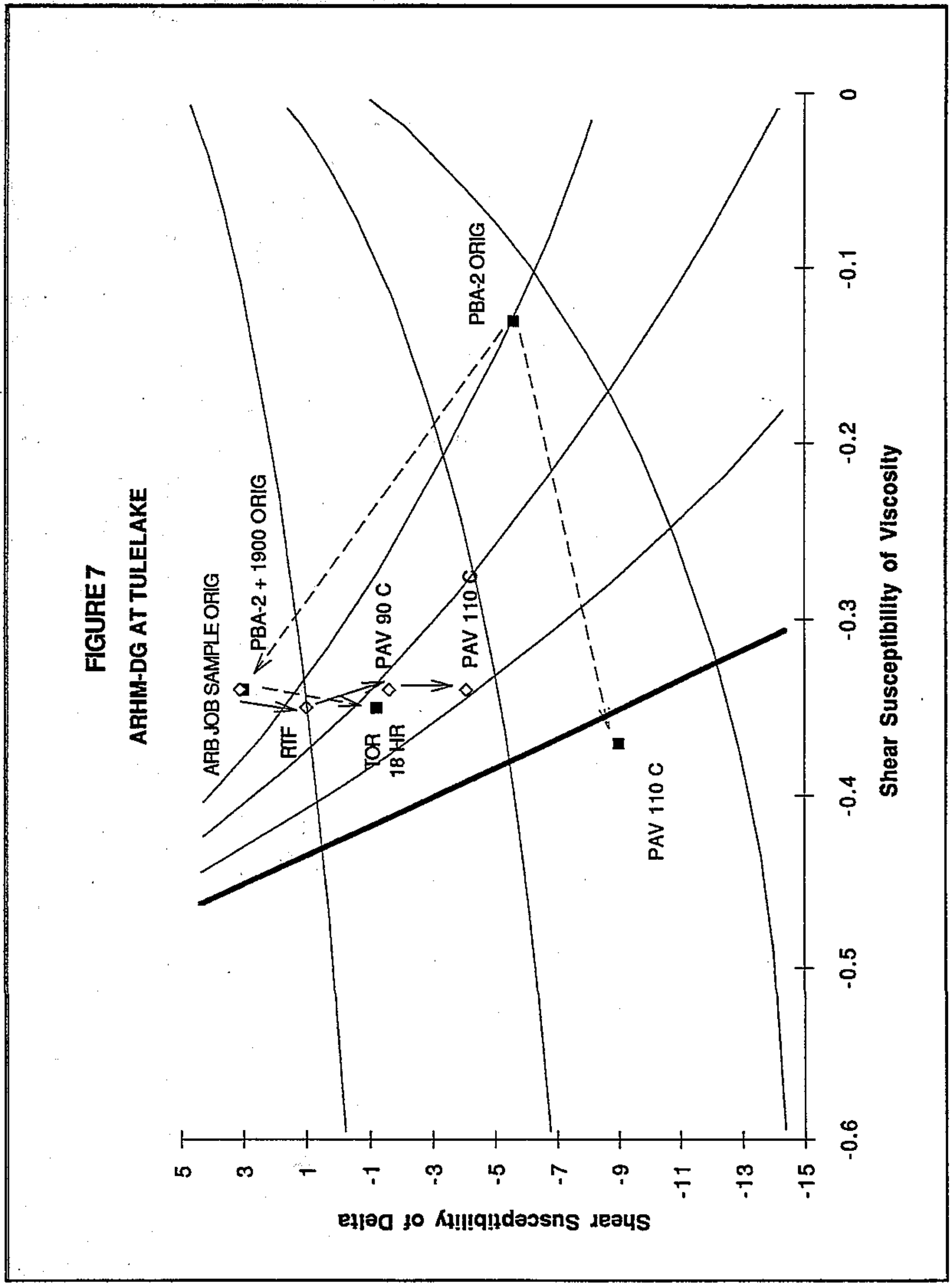



**FIGURE 7**
**ARHM-DG AT TULELAKE**

Fatigue cracking appeared in all of the ARB sections within three years. Coring indicates that the sections were built to design. However, dynaflect measurements indicate that the sections have been experiencing deflections far in excess of those on comparable sections at Ravendale. Therefore, the distress is due to a design consideration rather than a binder consideration.

**Round Valley**

This project using ARHM-GG was constructed in 1991 on Route 395 a few miles north of Bishop. The project consisted of several test sections 120 mm thick placed after milling 120 mm of DGAC from the original section of 150 mm AC. In the ARHM section, only 60 mm was milled and 60 mm ARHM-GG was then placed over a SAMI. Only a job sample of the ARB was analyzed. The data are presented in Figure 8 with the following observation:

1) The original binder has properties similar to those measured for the other projects reported herein, but upon aging with only the rolling thin film oven, there is a dramatically different horizontal shift to the left. This shift crosses the line of risk for fatigue cracking.

The ARHM-GG section on this project fatigue cracked in less than one year. The conclusion based on Figure 8 suggest that the ingredients used in the recipe resulted in an ARB that, upon relatively little aging, didn't have adequate internal compatibility.

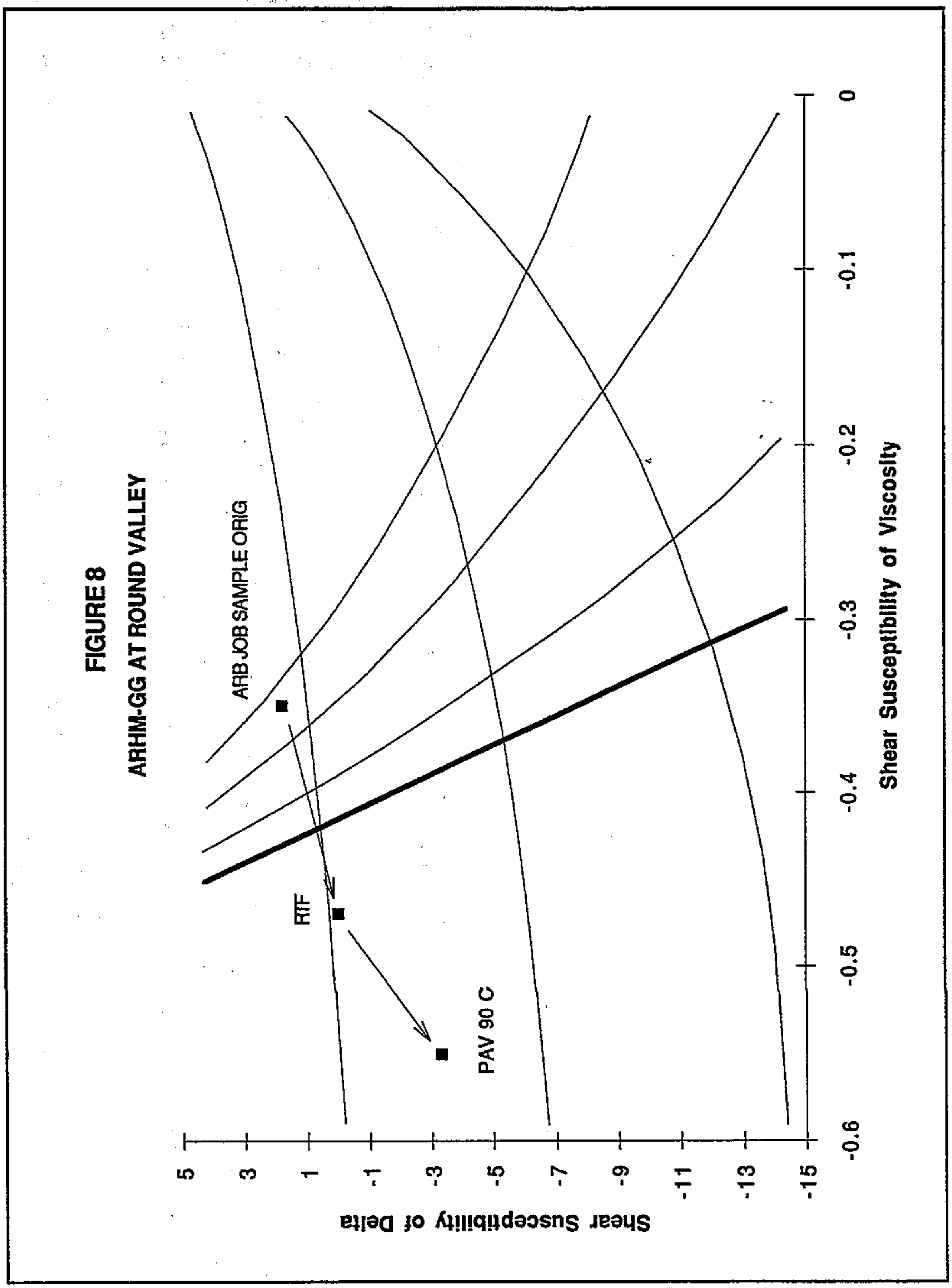



**FIGURE 8**
**ARHM-GG AT ROUND VALLEY**

**Newberry Springs**

This project was constructed in 1992 on Interstate 40 in the desert. There were several different materials and structural sections placed. Only the job sample of the ARB and the base AR-4000 used to make the binder were analyzed as presented in Figure 9. The observations from the data are:

1) The base asphalt is different from that used on the other projects studied. The shear susceptibility parameters suggest that the asphalt came from a California coastal crude source (2).

2) The aging of the ARB has the same horizontal shift to the left as that seen for the sample from the Round Valley project.

3) The location of the PAV residue relative to the line of risk suggests premature failure of the test sections containing this binder.

As of three years, there are reports of fatigue cracking on this project.

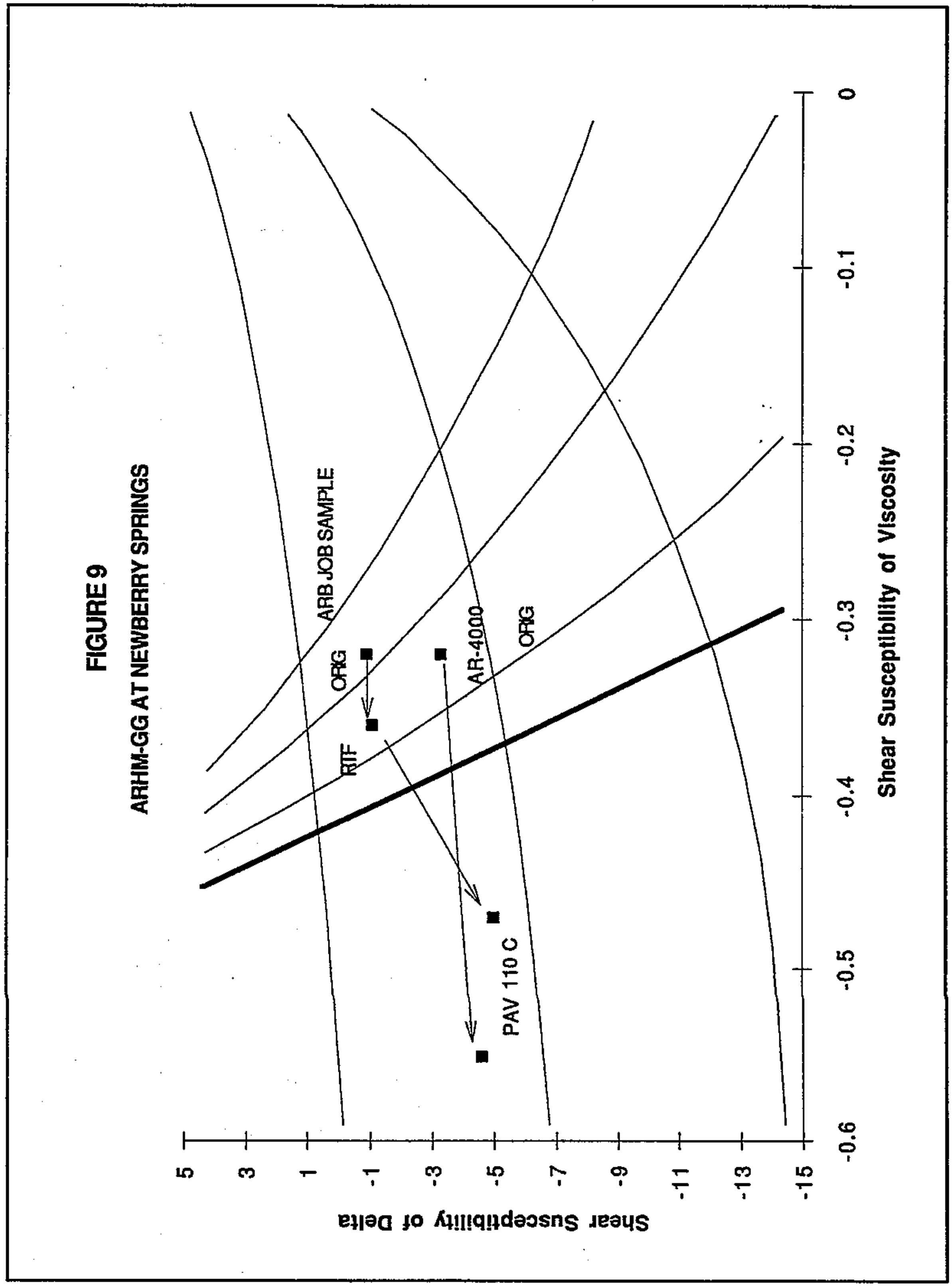


FIGURE 9
ARHM-GG AT NEWBERRY SPRINGS
Shear Susceptibility of Delta
Shear Susceptibility of Viscosity
ARB JOB SAMPLE
ORIG
RTF
AR-4000
ORIG
PAV 110 C
5
3
1
-1
-3
-5
-7
-9
-11
-13
-15
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0

**Wasco**

On this project, constructed in 1992, ARHM-GG was used in the entire overlay. From this project, the base AR-4000 and two differing samples of ARB were tested. The difference in ARB occurred because the manufacturer requested permission to use binder held-over for a longer period than allowed in the specifications. The contention was that this wouldn't harm the binder if the temperature was reduced to 120° C for the proposed 3 day hold-over period. It was agreed to allow this as long as the ARB was kept separate and its placement was recorded for long-term performance evaluation. Most of this occurred; however, the manufacturer blended in an additional 4 percent total rubber and then combined freshly blended binder, at a ratio of 1:4, with the reconstituted extended storage binder.

The rheological analysis of the original base, normal job binder, extended storage binder, and the aged residues of each was conducted and the data are shown in Figure 10 with the following observations:

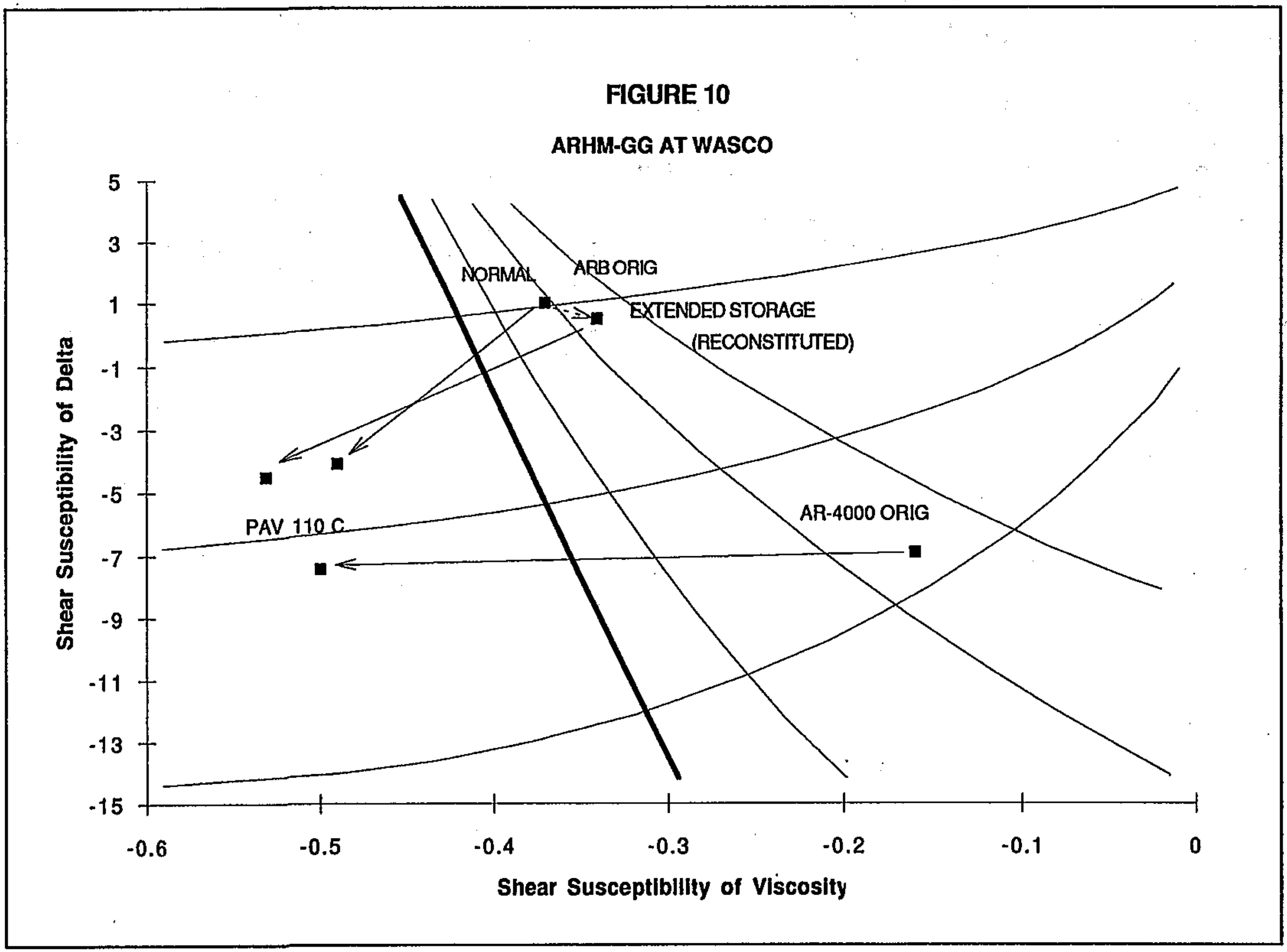


FIGURE 10
ARHM-GG AT WASCO
NORMAL
ARB ORIG
EXTENDED STORAGE
(RECONSTITUTED)
AR-4000 ORIG
PAV 110 C
Shear Susceptibility of Delta
Shear Susceptibility of Viscosity
5
3
1
-1
-3
-5
-7
-9
-11
-13
-15
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0

1) The routine job sample is uncharacteristically shifted to the left on the contours of increasing high molecular weight elastic structure.

2) The extended storage sample shows more of the expected relationship.

3) After aging, all of the binders are to the left of the line of risk.

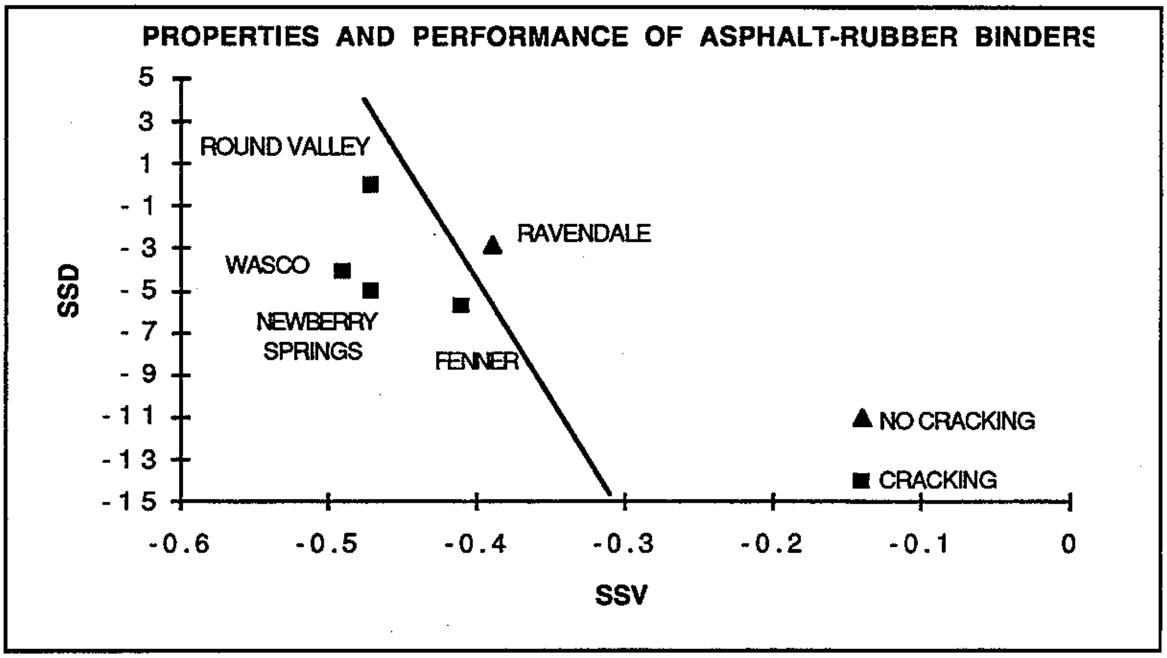
4) The aged residue of the routine ARB is in the expected location relative to the aged residue of the base AR-4000 (due to diffused rubber-based extender oil contribution).

5) The aged residue of the extended storage ARB is shifted significantly to the left of the routine material.

Between the second and third year, fatigue cracking appeared on this project.

**Summary Regarding Fatigue Properties**

As shown in the figure below a "line of risk" applied to the shear susceptibility parameters can be used to estimate the binder contribution to premature fatigue cracking of the pavement.



## Conclusions Regarding Fatigue Properties — Asphalt-Rubber Binder in ARHM-DG and ARHM- GG

- The shear susceptibility parameters are useful for understanding the multi-component binders obtained by blending paving asphalt, extender oil, and ground tire rubber.
- The same recipe doesn't necessarily yield the same binder properties.
- The "line of risk for fatigue cracking" is useful for differentiating between binders associated with acceptable pavement performance and those associated with unacceptable pavement performance.
- Extended storage can adversely effect binder properties.

## Recommendations Regarding Fatigue Properties — Asphalt-Rubber Binder in ARHM-DG and ARHM- GG

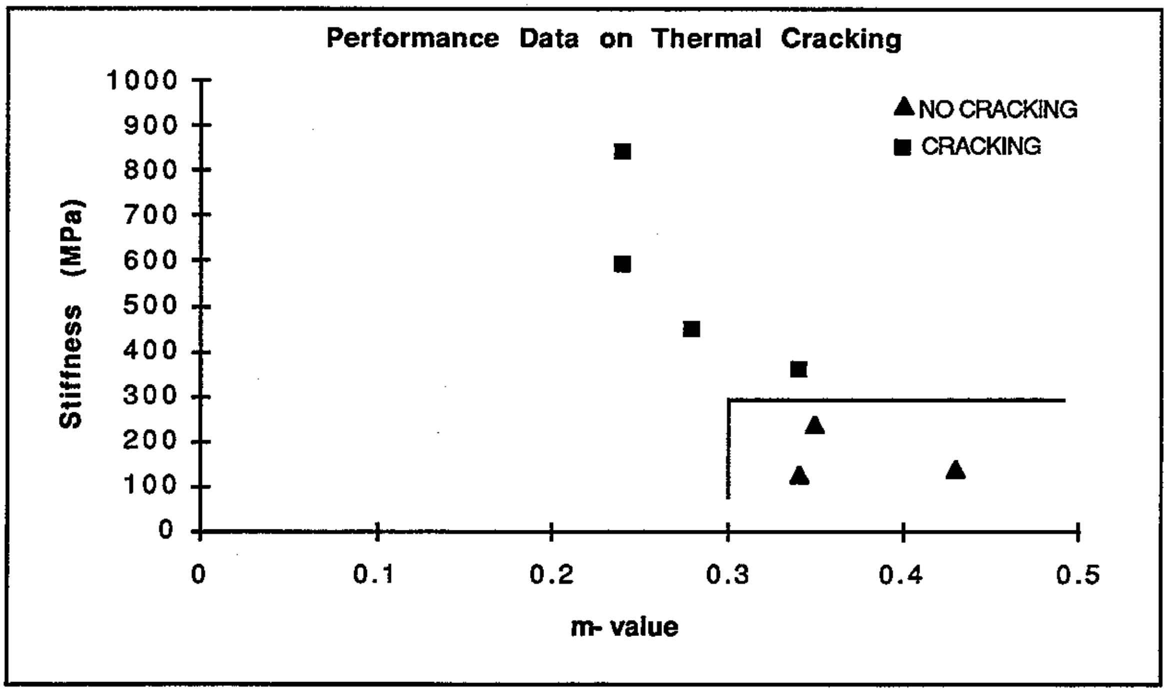
- The shear susceptibility parameters at 25° C of the residue from the climatically appropriate aging condition (either PAV or TOR) should be to the right of the "line of risk for fatigue cracking", described mathematically as:

$$SSD \geq -115\ (SSV) - 50.6$$

- The times and temperatures currently being used for asphalt-rubber binder production should continue to be used while the manufacturers evaluate the effect that these variables will have on their ability to meet the fatigue performance criteria described above.

### Thermal Cracking

The DSR can be used to obtain the low temperature properties of binders that strongly influence the thermal cracking resistance of the pavement (3). To accomplish this, a frequency sweep of 1 to 100 radians per second is run at the temperature at which G* is about 4 E+07 Pa at 1 radian per second. This temperature was -5° C for the Ravendale and Tulelake binders. A plot is then made of log G* vs. log time(seconds), where time = 1/frequency(w). The m-value is the slope of the curve at the stiffness value of interest. The current values being recommended are a maximum 2 hour creep stiffness of 300 MPa (equivalent dynamic stiffness is 100 MPa) and a minimum m-value of 0.30. Dynamic stiffness measurement temperatures are converted to creep stiffness (2-hr. loading) temperature by calculating : 5 • log(7200 • w) and subtracting this value from the measurement temperature (3). As shown in the figure below, data from Caltrans projects (8), with standard and polymer modified asphalts, supports these limiting values.

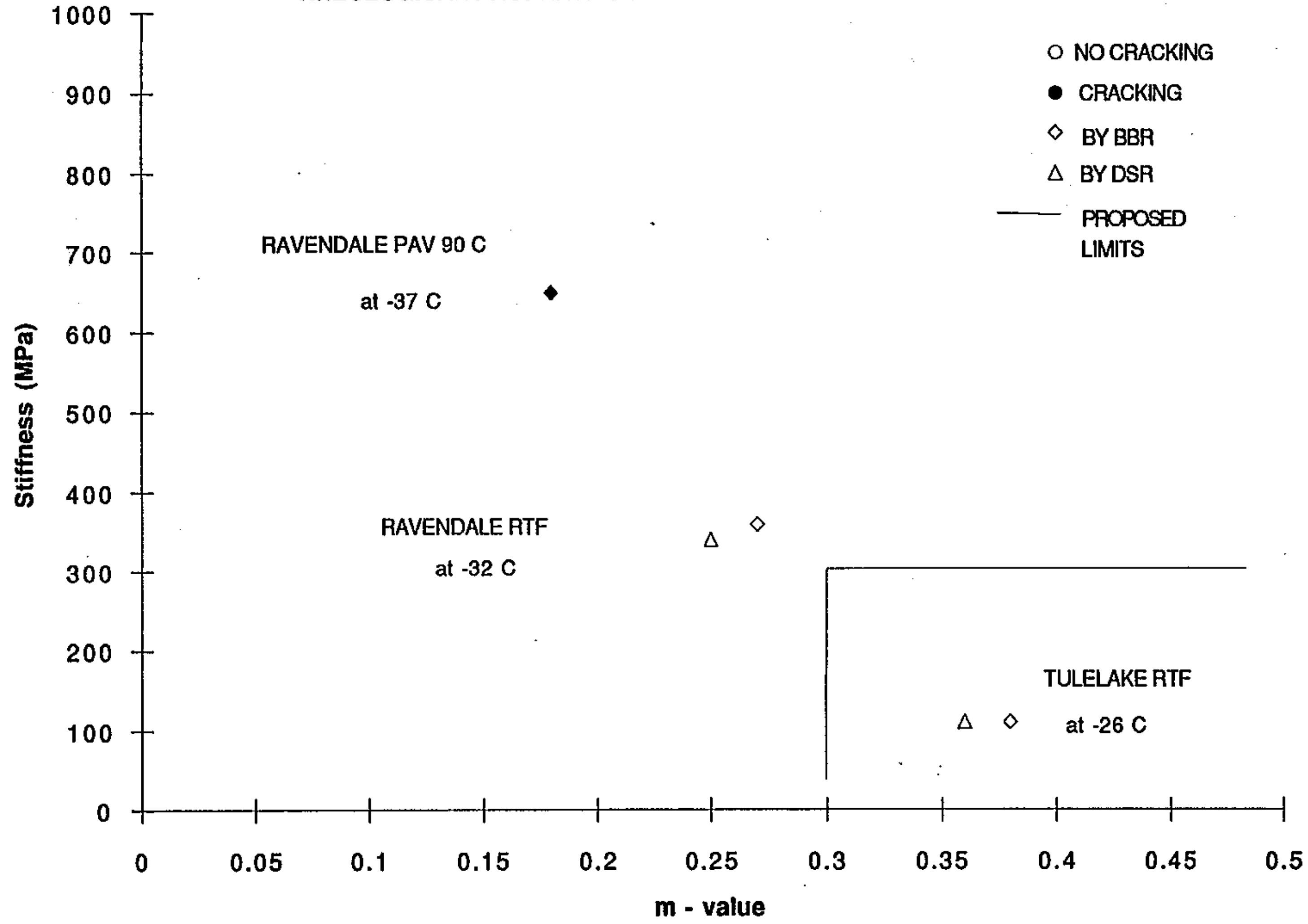


At Ravendale the minimum temperature in the second year was -32° C, (which did not result in any thermal cracking) so the stiffness and m-value were determined on the RTF residue for this exposure. During the sixth winter, the minimum temperature was -37° C. This exposure did result in thermal cracking. The properties were determined for this occurrence by testing the residue from PAV aging at 90° C. At Tulelake, the second winter (of -26° C) did not cause any thermal cracking. The properties of the RTF residue were determined for this exposure. The properties of these binders were also investigated using a Bending Beam Rheometer(BBR). However, the preparation of the thin beams required additional attention due to the relatively high viscosity asphalt-rubber binders. At 190° C, the binders are significantly more viscous than 30 wt.. oil (per AASHTO TP-1), so rodding the binder in the mold and reheating was necessary to obtain beams without visible air bubbles.

The properties and performance data for Ravendale and Tulelake are shown in Figure 11.

FIGURE 11

RHEOLOGICAL PROPERTIES RELATED TO THERMAL CRACKING



Notice that the two test methods yield essentially the same values. It is observed that the proposed SHRP values are conservative based on this data. It is on this basis that these values are being proposed for initial use in an asphalt-rubber binder specification.

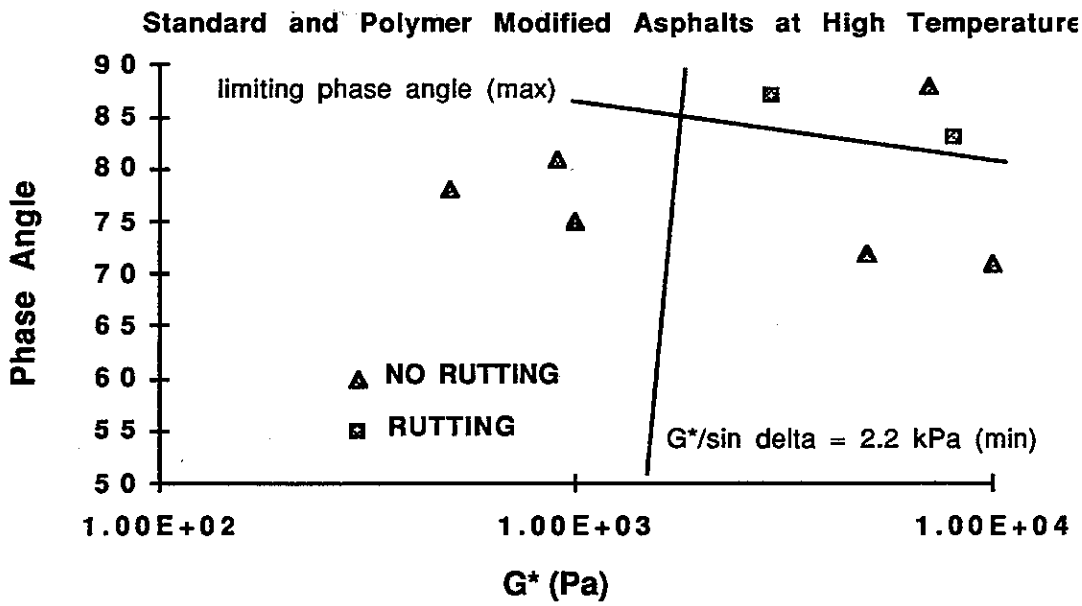
**Conclusions and Recommendations Regarding Thermal Cracking Properties — Asphalt-Rubber Binder in ARHM-DG and ARHM-GG**

- The properties of creep stiffness and m-value determined by rheological analysis correlate with transverse cracking.
- To obtain the desired thermal cracking resistance, determine the m-value and stiffness of the aged residue (either PAV or TOR) appropriate for the climate using either rheometer.
- The minimum m-value should be 0.30.
- The maximum creep stiffness should be 300 MPa.

**Rutting Resistance**

To determine the contribution of a binder to rutting resistance, G* and delta are measured at the highest expected pavement temperature (2). These properties are most important right after construction. Therefore, the RTF residue is tested. However, it needs to be understood that in the case of pavement stability, the properties of the binder should be minor relative to binder content, compaction, aggregate gradation, aggregate shape and moisture sensitivity of the mix.

The binder properties and pavement performance of projects (2) with standard and polymer modified asphalts are shown in the figure below.

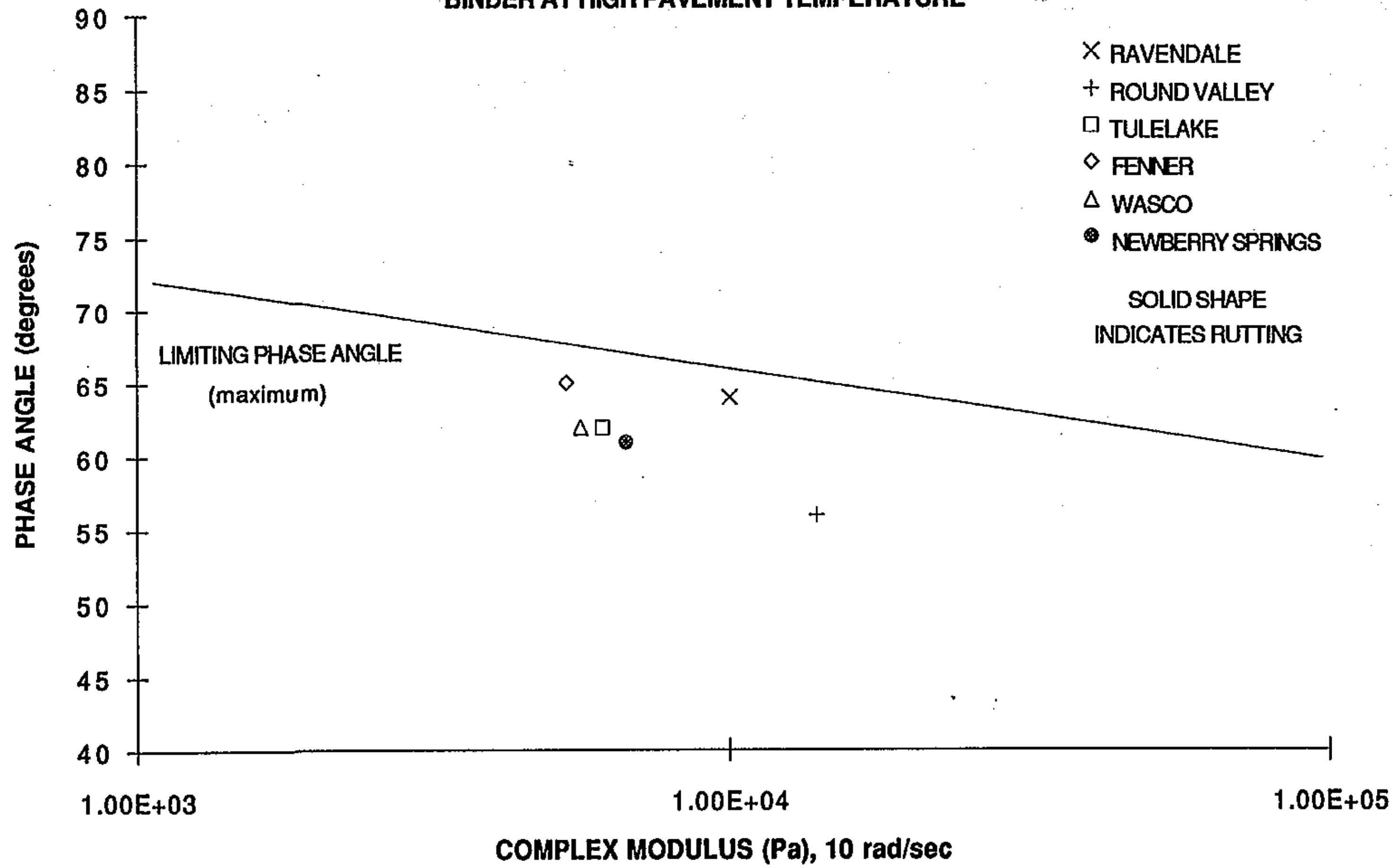



The "limiting phase angle" maximum was proposed in reference 2 as an indication of a binders potential to contribute to pavement stability. Binders with a large elastic component (smaller phase angle) provide additional resistance to permanent displacement. In reference 5, a minimum of 2.2 kPa is proposed for the value of G*/ sin delta. Note that neither of these approaches always correctly predict the development of rutting. As mentioned above, this is because rutting is governed more by the net mix properties than by binder properties.

While keeping this in mind, the asphalt-rubber binder properties and pavement performance data are presented in Figure 12.

FIGURE 12

PROPERTIES AND PERFORMANCE OF ASPHALT-RUBBER BINDER AT HIGH PAVEMENT TEMPERATURE



Note the large elastic component of the asphalt-rubber binders relative to those of the standard and polymer modified asphalts shown in the previous figure. Note again that the high temperature binder properties don't always correlate with rutting resistance. This suggests that pre-job decisions on the ability of a pavement to resist rutting should come from a performance based mix test only. The high temperature binder properties are still of interest, but maybe only for flagging projects that should receive extra scrutiny regarding the mix. There is evidence (9,10) that some asphalt-rubber blends can have the same properties as standard paving asphalts at 65° C to 70° C (phase angles > 85°). Since there isn't any performance data on such binders, and the experience to date has been with binders having a large elastic component, a limiting phase angle equation should be used until there is evidence that justifies expansion of the envelope.

## Conclusions Regarding Rutting Resistance Properties — Asphalt-Rubber Binder for ARHM-DG and ARHM-GG

- G* and phase angle are not, by themselves, performance based properties sufficient to preclude rutting.
- The contribution to rutting resistance of high-modulus low-phase angle asphalt-rubber binders is desirable.

## Recommendation Regarding Rutting Resistance Properties — Asphalt-Rubber in ARHM-DG and ARHM-GG

The limiting phase angle line, described mathematically as: Phase Angle (maximum) = 90 - 6 • log G* should be used as the specification limit for the RTF residue measured at the highest expected pavement temperature at a frequency of 10 radians per second.

## FORMULATION VARIABLES ANALYSIS

Studies were conducted using the shear susceptibility parameters at 25° C to examine the effect of the following:

A) Rubber content, from 5 percent to 25 percent of the total binder.

B) Reaction time, from 5 minutes to 45 minutes.

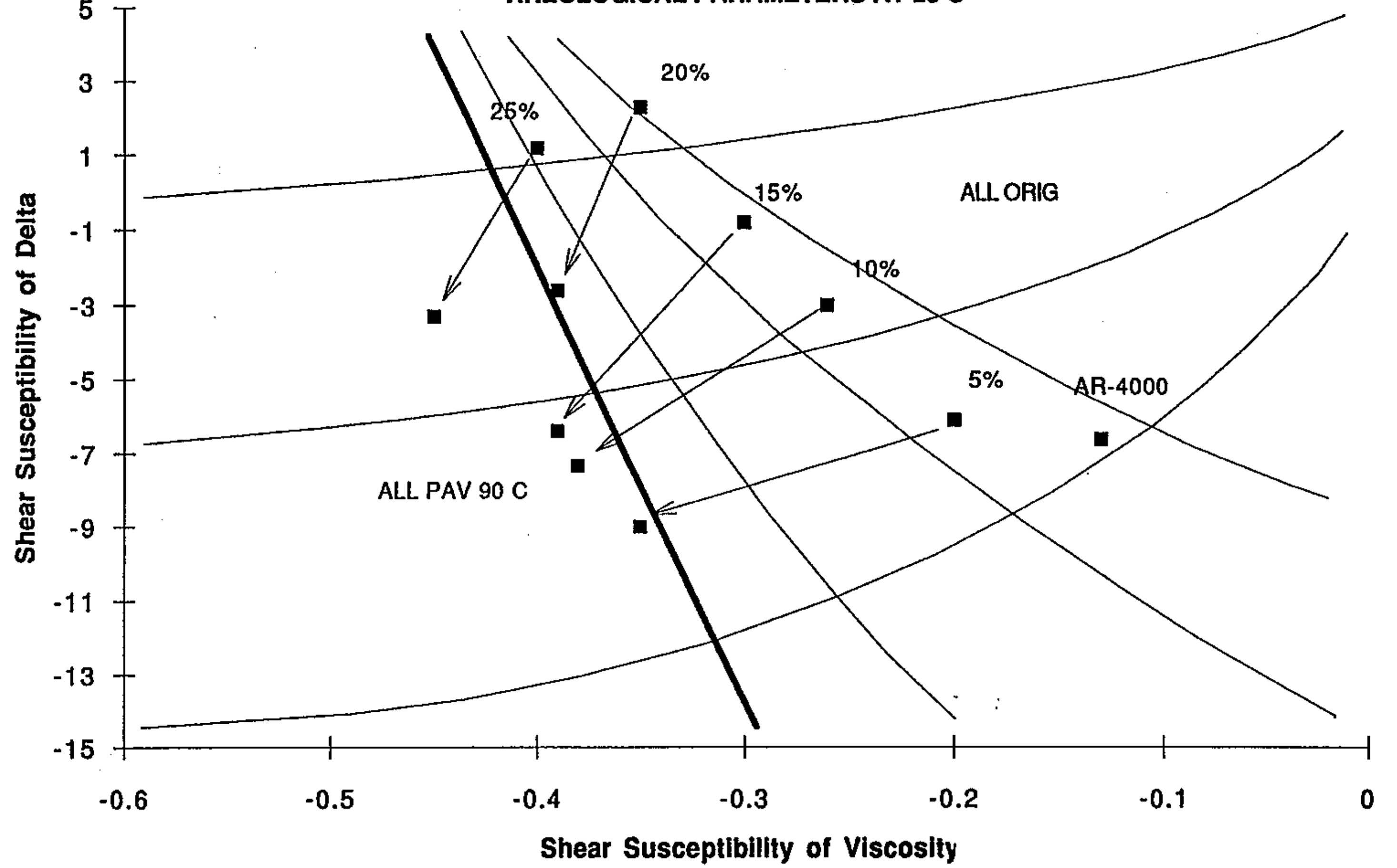
The materials used in these studies consisted of a Paramount AR-4000 paving asphalt, Atlos 1103 ground tire rubber, and Atlos C-112 ground natural rubber.

### Rubber Content

Blends were made of 5, 10, 15, 20, and 25 percent rubber by total weight. The total rubber was a blend of 80 percent 1710 and 20 percent C-112. Each blend was reacted for 45 minutes at 190° C (± 10° C). The original binders and the PAV residues (90° C) were tested and the data are displayed in Figure 13.

**FIGURE 13**

**EFFECT OF VARIABLE RUBBER CONTENT ON RHEOLOGICAL PARAMETERS AT 25 C**



The observations are:

1) The normal rubber content (20 to 23 percent) results in a binder property above the line through SSD = 0.

2) As the rubber content is increased to 20 percent, the shift to the right is evident from the extender oil diffusion seen earlier.

3) Up to 20 percent the net change in binder property appears linear with respect to increasing rubber content.

4) Up to 20 percent the aged binder properties roughly parallel the line of risk.

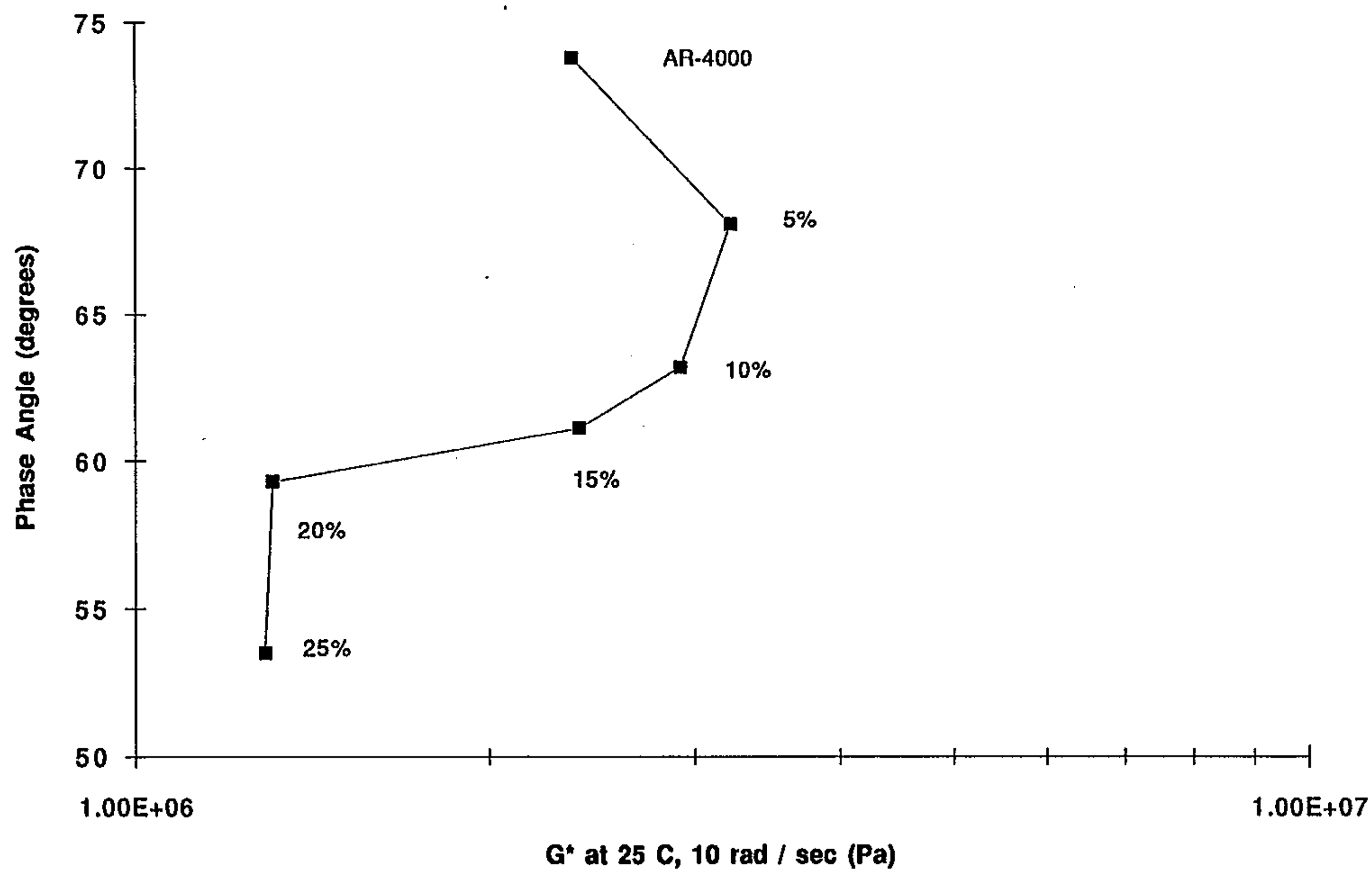
5) At 25 percent, the susceptibility of the phase angle to shear rate changes dramatically. This change is directly toward the line of risk for fatigue cracking.

6) The shift seen at 25 percent rubber on original binder properties carried over directly in the aged residue properties. Note that 20 percent appears to be a good choice relative to the line of risk.

While this analysis of shear susceptibility data yields an observation of ground tire rubber based extender oil diffusing into the asphalt, the effect normally reported (9) during "reaction" is not apparent. The reported swelling of the rubber particles due to diffusion of the lower molecular weight asphalt constituents during reaction should produce a stiffer binder. Thus, the G* vs. phase angle values at one frequency (10 rad/sec) were reviewed for stiffness trends within the variable rubber content data set. As shown in Figure 14, an increase in stiffness is apparent at the lower rubber contents. However, at the higher rubber contents, the binders are softer than the base asphalt.

## FIGURE 14

**EFFECT OF VARIABLE RUBBER CONTENT ON COMPLEX MODULUS**



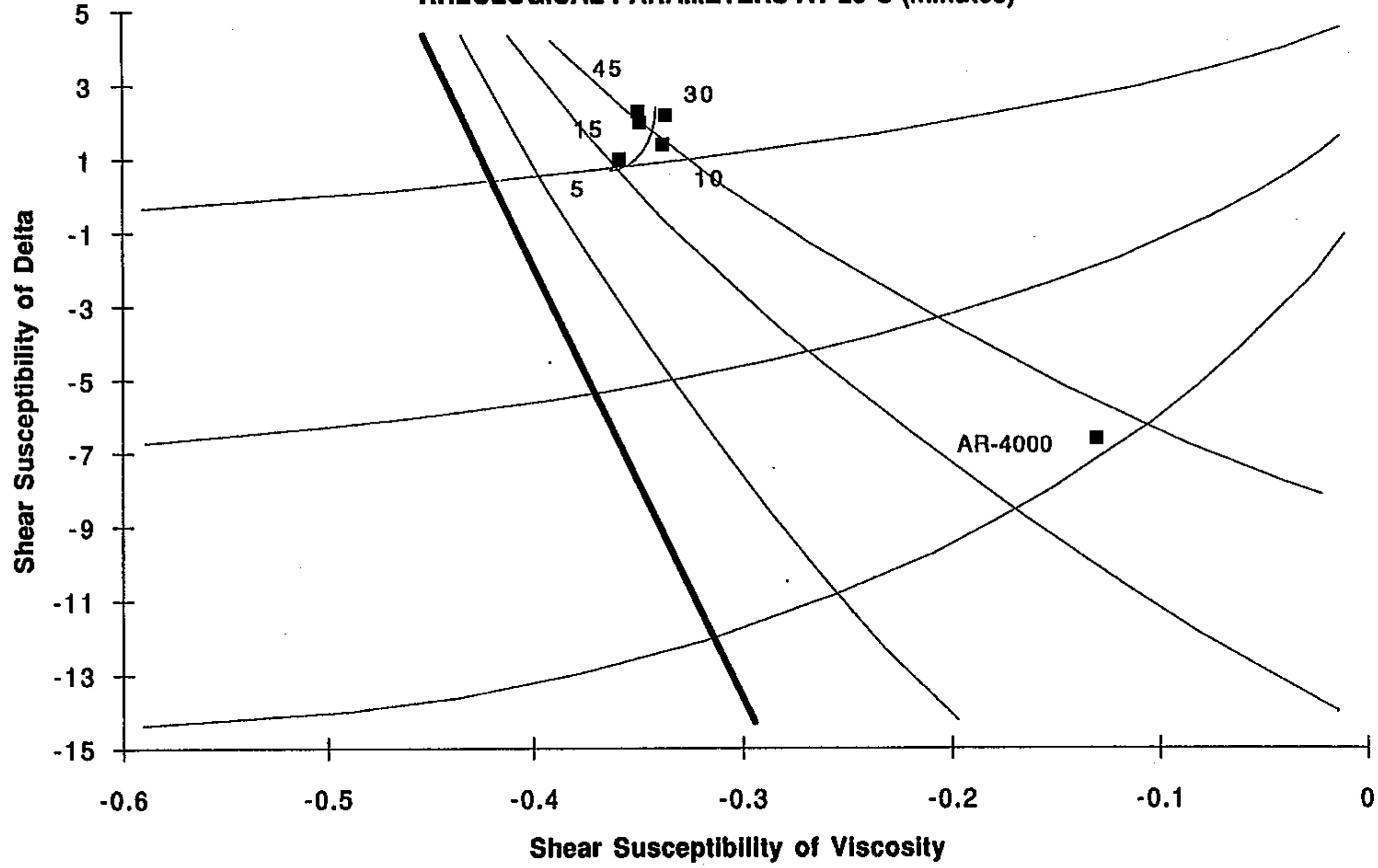
Therefore, it appears that there are opposing diffusion paths during the "reaction" process. It also appears that in the normal range of rubber contents being used (i.e., about 20 percent), the net binder modulus is softer due to the diffusion of rubber-based extender oil into the base asphalt.

**Reaction Time**

Several of the previous experiments have shown rubber-based extender oil diffusion by altering the ingredient concentrations. Diffusion is also time dependent. Therefore, a blend was made of the above ingredients at 20 percent rubber with samples removed from the blending vessel at 5, 10, 15, 30, and 45 minutes. SSD and SSV were determined for each of these and plotted in Figure 15, yielding the following comments:

**FIGURE 15**

**EFFECT OF VARIABLE REACTION TIME ON RHEOLOGICAL PARAMETERS AT 25 C (minutes)**



1) The shift from left to right due to a softer base asphalt being created by the diffusion of the extender oil is clear.

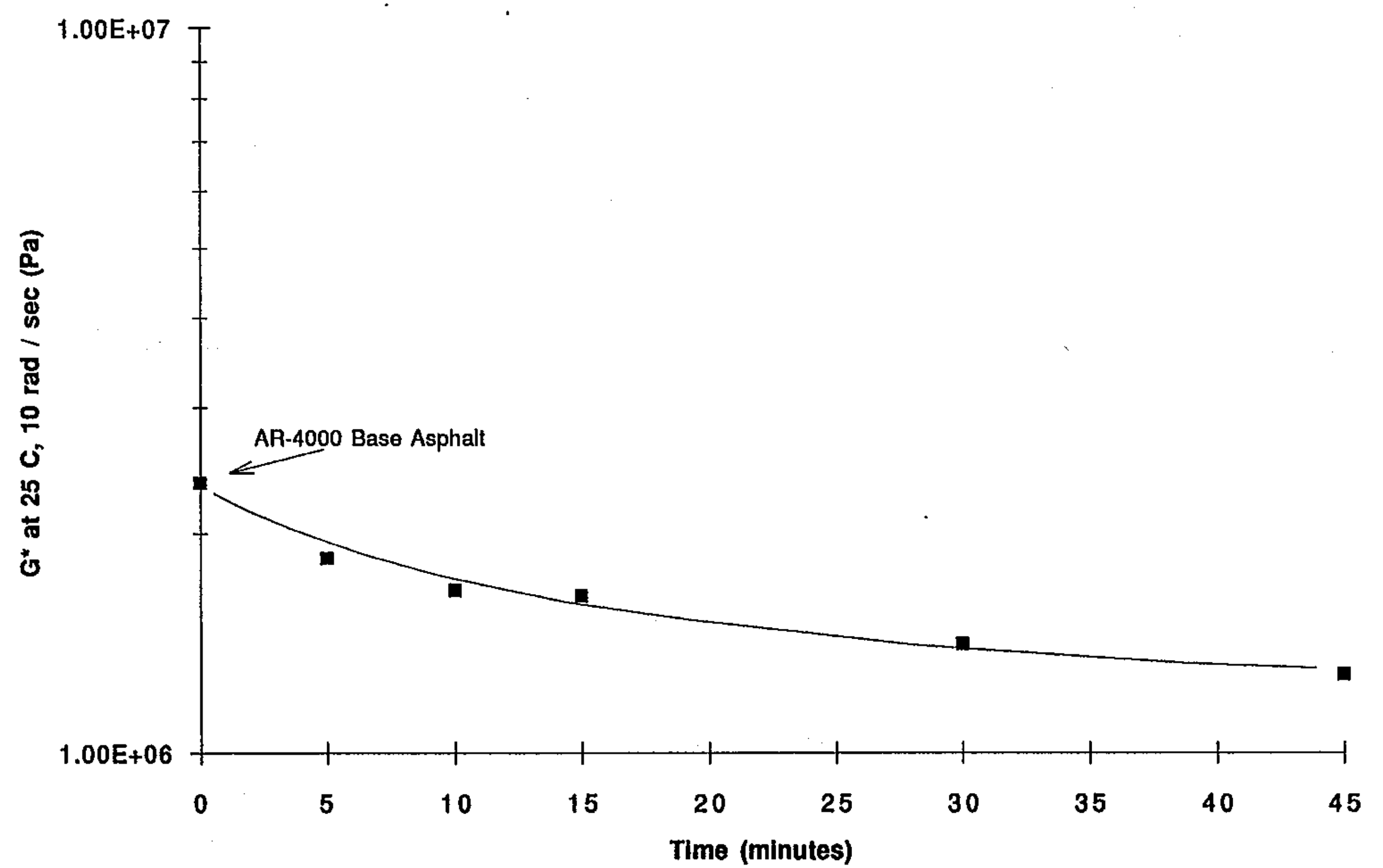
2) It appears that the 5 minute initial blending period was too long to capture just the property change due to the addition of the high molecular weight elastic structure.

3) The majority of the diffusion occurred in the first 10 minutes.

4) During the reaction period there was a small but obvious increase in the high molecular weight elastic structure.

The changes in G* vs. time at 10 radians per second were also reviewed from this data set. As shown in Figure 16, a decrease in modulus is observed, further supporting the hypothesis of extender oil diffusion from the ground tire rubber.

FIGURE 16
EFFECT OF VARIABLE REACTION TIME ON COMPLEX MODULUS
( AR-4000 AND 20% RUBBER AT 190 C )



## CONCLUSIONS

- The physical properties of an asphalt-rubber binder can be characterized by using a dynamic shear rheometer with an appropriate sample geometry.
- The rheological properties studied can properly characterize the binder related pavement performance criteria at low and medium temperatures.
- The rheological properties studied at high temperatures are useful, but by themselves should not be the basis for decisions on rutting resistance.
- Tire-based extender oil diffuses into the base asphalt during the reaction process.
- Solvent recovery of asphalt-rubber binder yields material that misrepresents the binder properties in the pavement from which it was taken. Therefore, asphalt-rubber binders should not be recovered in this manner for the purposes of studying aging or performing a recycle design.
- The risk of not obtaining the desired asphalt-rubber binder properties is greater with the current recipe specification than with a physical property specification based on testing with a DSR. Compliance with the recipe specification provides no assurance that the binder has the necessary resistance to cold temperature cracking. Similarly, it is also risky to place recipe binder in the desert without determining the aging characteristics. The risk of proceeding with a physical property specification is only that the limiting value might need fine tuning based on performance data that may be available several years from now. This is why initial use of the new specification should begin as soon as possible.

## RECOMMENDATIONS

- The rheology-based specifications shown on Page 46 should be tried on several projects, particularly those located in severe climate areas.
- The rheological properties of the binders used on several asphalt concrete projects should be measured. This should include projects on which asphalt-rubber recipe specifications are used as well as projects that do not include asphalt rubber. The performance of all these pavements should then be documented.

## IMPLEMENTATION

- The Caltrans Office Engineer will be asked to create a Standard Special Provision containing the asphalt-rubber binder specifications shown on Page 46.
- The Office of Materials Engineering and Testing Services will work with the asphalt-rubber producers regarding approval to supply these materials to Caltrans projects by Certificate of Compliance.
- The Districts will be asked to include the new specifications in several upcoming projects with emphasis on jobs in severe climate locations.
- The Office of Materials Engineering and Testing Services will document the performance of pavements for which the rheological properties of the binder are measured.

## MODIFIED BINDER (MB) GRADES FOR ASPHALT-RUBBER HOT MIX

| | Environmental Guidelines for Selecting Grade | Moderate | Cold | Very Cold | Hot | Hot/Cold | Hot/Very Cold | Very Hot |
|---|---|---|---|---|---|---|---|---|
| | Lowest Recorded Temperature | > -18°C (0°F) | > -29°C (-20°F) | > - 40°C (-40°F) | > -18°C ( 0°F) | > -29°C (-20°F) | > - 40°C (-40°F) | > - 18°C (0°F) |
| | Average of Daily Maximum Temperature in July | < 32°C (90°F) | < 32°C (90°F) | < 32°C (90°F) | < 38°C (100°F) | < 38°C (100°F) | < 38°C (100°F) | > 38°C (100°F) |
| **Specification Value (1)** | **Test Method** | **MB-1** | **MB-2** | **MB-3** | **MB-4** | **MB-5** | **MB-6** | **MB-7** |
| On Original Binder<br>SSD ≥ 30 (0.7 + SSV)³ | CT 381 | 25°C | 25°C | 25°C | 25°C | 25°C | 25°C | 25°C |
| On Residue from RTF Oven | AASHTO T-240 | | | | | | | |
| Delta ≤ 90 -6 log G* | CT 381 | 58°C | 58°C | 58°C | 64°C | 64°C | 64°C | 70°C |
| On Residue from PAV @:<br>Or | AASHTO PP1 | 90°C | 90°C | 90°C | 100°C | 100°C | 100°C | 110°C |
| @ 113°C for Residue from Tilt-Oven: | CT 374 B | 18 hrs. | 18 hrs. | 18 hrs. | 36 hrs. | 36 hrs. | 36 hrs. | 72 hrs. |
| Stiffness: Either,<br>300 MPa (maximum), @ 60 sec | AASHTO TP1 | -8°C | -19°C | -30°C | -8°C | -19°C | -30°C | -8°C |
| Or<br>100 MPa (maximum), @ 10 rad/sec | CT 381 | 9°C | -2°C | -13°C | 9°C | -2°C | -13°C | 9°C |
| m-value: 0.30 minimum | TP1 or CT 381 | | | | | | | |
| SSD ≥ -115 (SSV) -50.6 | CT 381 | 25°C | 25°C | 25°C | 25°C | 25°C | 25°C | 25°C |

SSD = Shear susceptibility of Delta
SSV = Shear susceptibility of Viscosity

(1) Determined at condition in table.

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2) R. E. Reese and J. L. Goodrich, "California Desert Test Road — A Step Closer to Performance Based Specifications," Journal of the Association of Asphalt Pavement Technologists, Vol. 62, 1993.

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10) H. Bahia and R. Davies, "Effect of Crumb Rubber Modifiers on Performance Related Properties of Asphalt Binders," Journal of the Association of Asphalt Paving Technologists," Vol. 63, 1994.

# APPENDIX A

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RHEOLOGY OF ASPHALTS

by

JOSEPH L. GOODRICH

September 8, 1991

The following is excerpted and edited from:

"Asphalt and Polymer Modified Asphalt Properties Related to the Performance of Asphalt Concrete Mixes," J. L. Goodrich, Annual Meeting of the Association of the Asphalt Paving Technologists, 1988.

*Asphalt Rheology:*

Classic theory defines an elastic solid (e.g., a spring) as a material which exhibits stress in proportion to the strain, but not in proportion to the rate of strain. On the other extreme are perfectly viscous (Newtonian) fluids which exhibit stress in proportion to the rate of strain but not to the amount of strain.

A viscoelastic material, such as asphalt, exhibits both viscous and elastic behavior and displays a time dependent relation between an applied stress and the resultant strain. Within the linear viscoelastic region of an asphalt, the interrelation of stress and strain is influenced by time alone, and not by the magnitude of the stress.

Many researchers have established that within certain strain boundaries, asphalt and asphalt concrete are both linear viscoelastic materials.

When a viscoelastic liquid, such as asphalt, is forced to move some of the input energy is lost to heat caused by the friction of viscous flow. At the same time some of the input energy is stored and released like a spring when then loading stops. This can be seen in a simple shear experiment (i.e. cone and plate). When the applied load is removed from the rotating cone, the spindle may return the stored energy by springing back slightly.

*Dynamic Mechanical Analysis:*

In our dynamic experiments, sinusoidal shear strains were imposed on asphalt samples. The samples of asphalt were placed between two parallel disks. When asphalt is cold and brittle, it may behave as a nearly ideal solid: the stress will exactly follow the sinusoidal input strain. At elevated temperatures, most conventional asphalts will approach ideal liquid (Newtonian) behavior. In this case the maximum stress will occur when the rate of strain is greatest. This occurs 90° out-of-phase with the peak strain. Therefore, with ideal liquids the peak stress lags 90° behind the peak input strain (**Figure 1**).

Between the ideal elastic solid behavior and the ideal viscous fluid response are the <u>viscoelastic</u> materials, such as asphalt. Depending on the temperature and strain frequency, the peak stress of viscoelastic materials can lag anywhere from 0° to 90° behind the maximum applied strain (**Figure 2**). The lag, or phase shift angle, is referred to as $\delta$ (**Figure 3**).

By varying the frequency of the input sinusoidal strain, the time-dependent viscoelastic behavior of an asphalt can be easily measured. That is, the balance between the viscous nature and the elastic nature of an asphalt can be measured as a function of frequency or temperature.

If the dynamic testing is done using small strains (within the linear viscoelastic region) the data obtained at higher and lower temperatures can be equated simply and graphically with lower and higher frequencies, respectively. Conversely data obtained at higher and lower frequency can be transposed into lower and higher temperatures, respectively. This is according to the principle of superposition which has been applied to asphalt by many researchers, and to asphalt concrete.

This superposition principle represents a powerful and convenient tool for evaluating dynamic loading data. An example of time (frequency)-temperature superposition is Figures 5 and 6. **Figure 5** shows the actual data points obtained over a range of temperatures and a narrow range of frequencies. By applying the superposition principle, each data set obtained at a particular temperature can be shifted along the frequency axis to form a smooth curve (**Figure 6**). The degree to which succeeding curves must be shifted to form a smooth curve is referred to as the shift factor (**Figure 7**), and is related to the temperature susceptibility of the material.

Notice in **Figure 6** that at very low frequencies the slope of the curve approaches a 45° angle. This is the region of frequency (or temperature) where the flow properties of the conventional asphalt exhibits Newtonian behavior. It is in this area that simple shear (e.g., cone and plate, sliding plate) and dynamic tests have been found to coincide.

*Rheological Parameters:*

In dynamic mechanical analysis the peak stress, the peak strain and the phase relationship between the stress and strain are measured. All of the rheological parameters are determined from these data.

- The ratio of the peak stress to the peak strain is the absolute value of the modulus. This is referred to as the complex shear modulus, $|G^*|$, and is named "G-star" (**Figure 2**):

$$|G^*| = \text{peak stress/peak strain} \qquad \text{Eq. 1}$$

- The elastic, in-phase component of $|G^*|$ is called the shear storage modulus, or G' (named "G-prime"). The storage modulus equals the stress in phase with the strain divided by the strain (**Figure 3**), or:

$$G' = |G^*| \cos \delta \qquad \text{Eq. 2}$$

  $\delta$ (or "delta") is the phase shift angle between the applied maximum strain and the maximum stress.

- The viscous, out-of-phase component of $|G^*|$, is called the shear loss modulus, or G" (named "G-double prime"). G" represents the viscous component of $|G^*|$. The loss modulus equals the stress 90° out of phase with the strain divided by the strain (**Figure 3**), or

$$G'' = |G^*| \sin \delta \qquad \text{Eq. 3}$$

Typical units for $|G^*|$, G' and G" are Pascals (SI), dynes/cm$^2$ (cgs), or psi.

- The complex dynamic shear viscosity, $|\eta^*|$ (called "eta-star"), is computed from the complex shear modulus and the strain frequency, $\omega$ (radians/sec) (**Figure 2**):

$$|\eta^*| = |G^*| / \omega \text{ (poise)} \qquad \text{Eq. 4}$$

Dynamic mechanical analysis has been used to determine the moduli of the binder and the relationship of the moduli to mix and pavement performance. In this study it has been found that the ratio of the viscous to the elastic moduli of an asphalt, referred to as the loss tangent, correlates well with its performance in dense graded asphalt concrete mixes.

- The loss tangent is the ratio of energy lost to the energy stored in a cyclic deformation (**Figure 3**):

$$\text{Loss tangent} = \tan \delta = G''/G' \qquad \text{Eq. 5}$$

Another way to visualize the relationship between the rheological parameters is seen in **Figure 4**. In the figure the elastic modulus (G') is plotted as a vector with a 0° phase angle; the viscous modulus (G") is plotted as a vector with a 90° phase angle. The complex shear modulus (G*) is the vector sum of G' and G". Thus G* is seen as a vector with a phase angle equal to δ. Notice that the ratio G"/G' is equal to the tangent of δ. Thus the name "tan δ" is given to this ratio. To describe the rheological properties of an asphalt the complex shear modulus, G* (or dynamic shear viscosity) <u>and</u> tan δ are <u>both</u> needed.

*Rheological Parameters versus Asphalt Concrete Performance:*

Particularly useful in defining the performance-related properties of asphalt binders are:

Low Temperature Thermal Cracking:

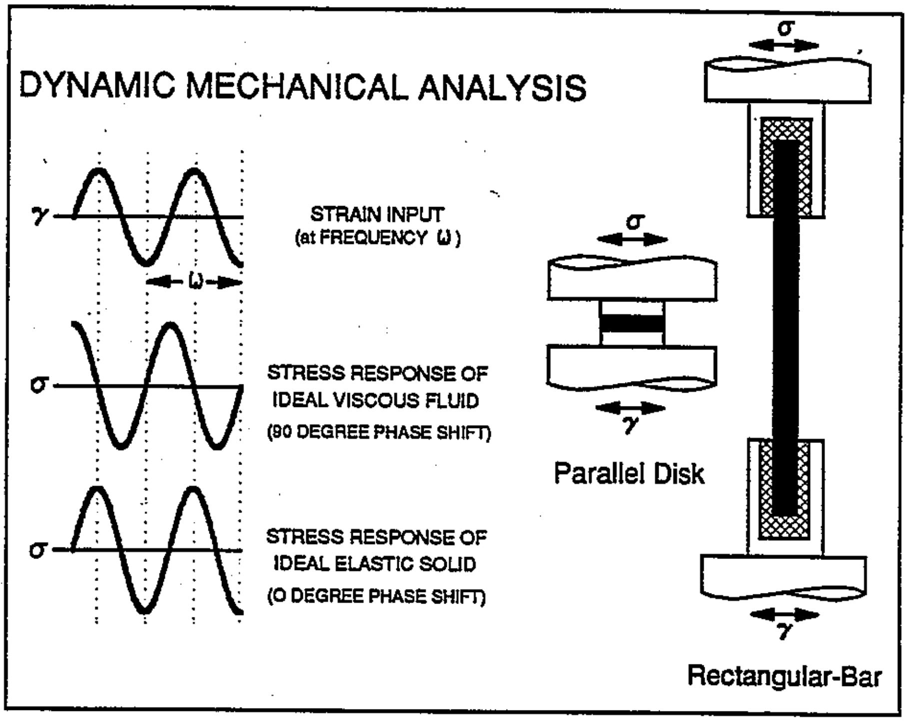
a. the temperature at which the asphalt becomes glassy (a brittle elastic solid) at a given frequency. This is defined by the peak in the viscous modulus, G" (**Figure 8**).

Fatigue and Permanent Deformation:

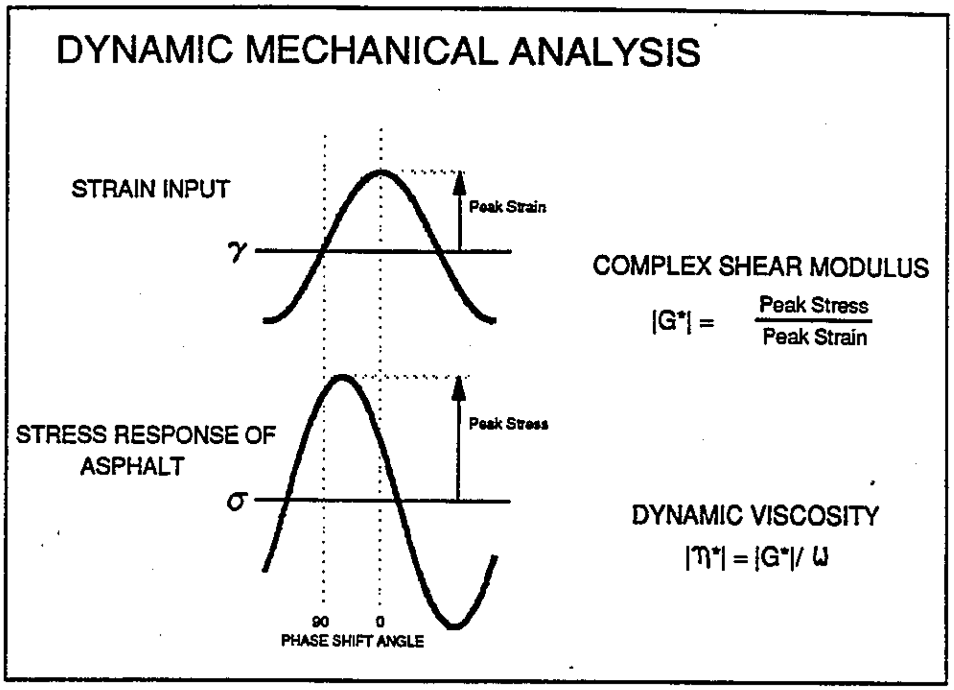
a. the ratio of G" to G' (that is the Loss Tangent) at a temperature of interest, together with
b. the dynamic viscosity (that is "eta-star") at the temperature of interest.

A low loss tangent within a range of dynamic viscosity relates to resistance to fatigue cracking and rutting, to the extent that a binder can influence these mix performance properties.

**FIGURE 1**


DYNAMIC MECHANICAL ANALYSIS
STRAIN INPUT
(at FREQUENCY ω)
STRESS RESPONSE OF
IDEAL VISCOUS FLUID
(90 DEGREE PHASE SHIFT)
STRESS RESPONSE OF
IDEAL ELASTIC SOLID
(0 DEGREE PHASE SHIFT)
Parallel Disk
Rectangular-Bar

## FIGURE 2




## FIGURE 3

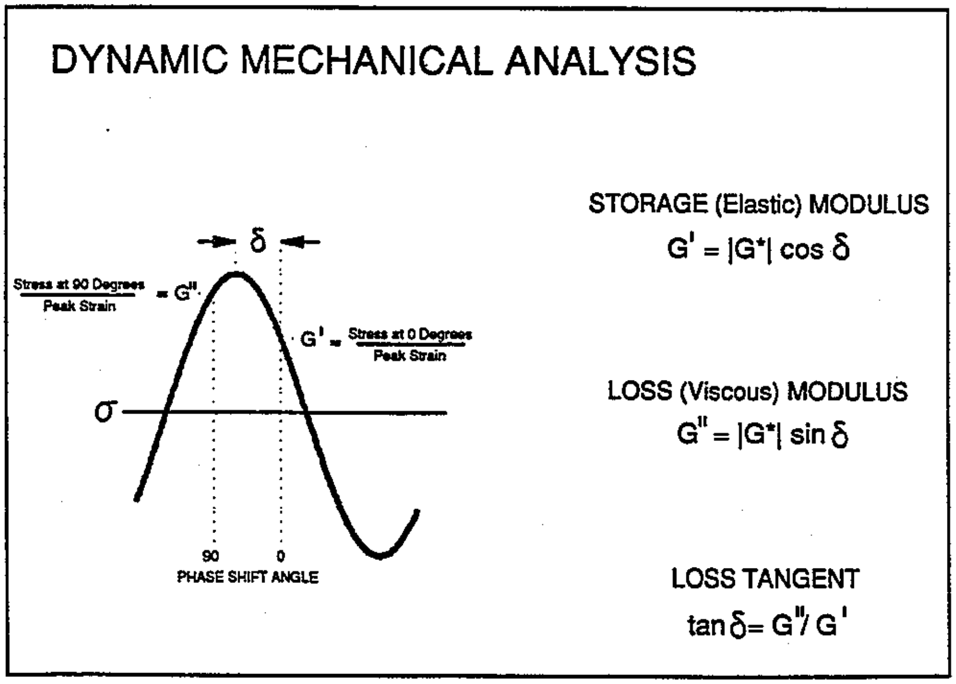
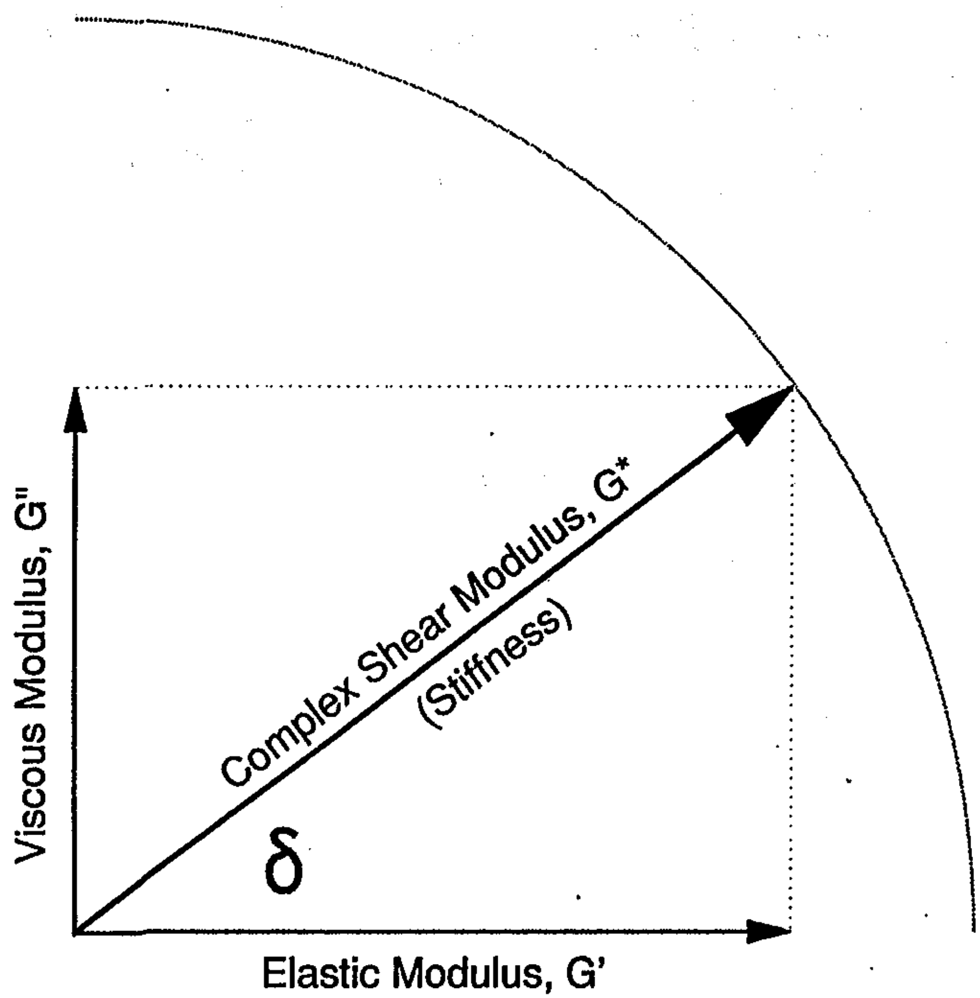


**FIGURE 4**

**Stiffness alone does not characterize performance-related asphalt rheology: stiffness and the ratio of G" to G' (tan δ) are both needed.**

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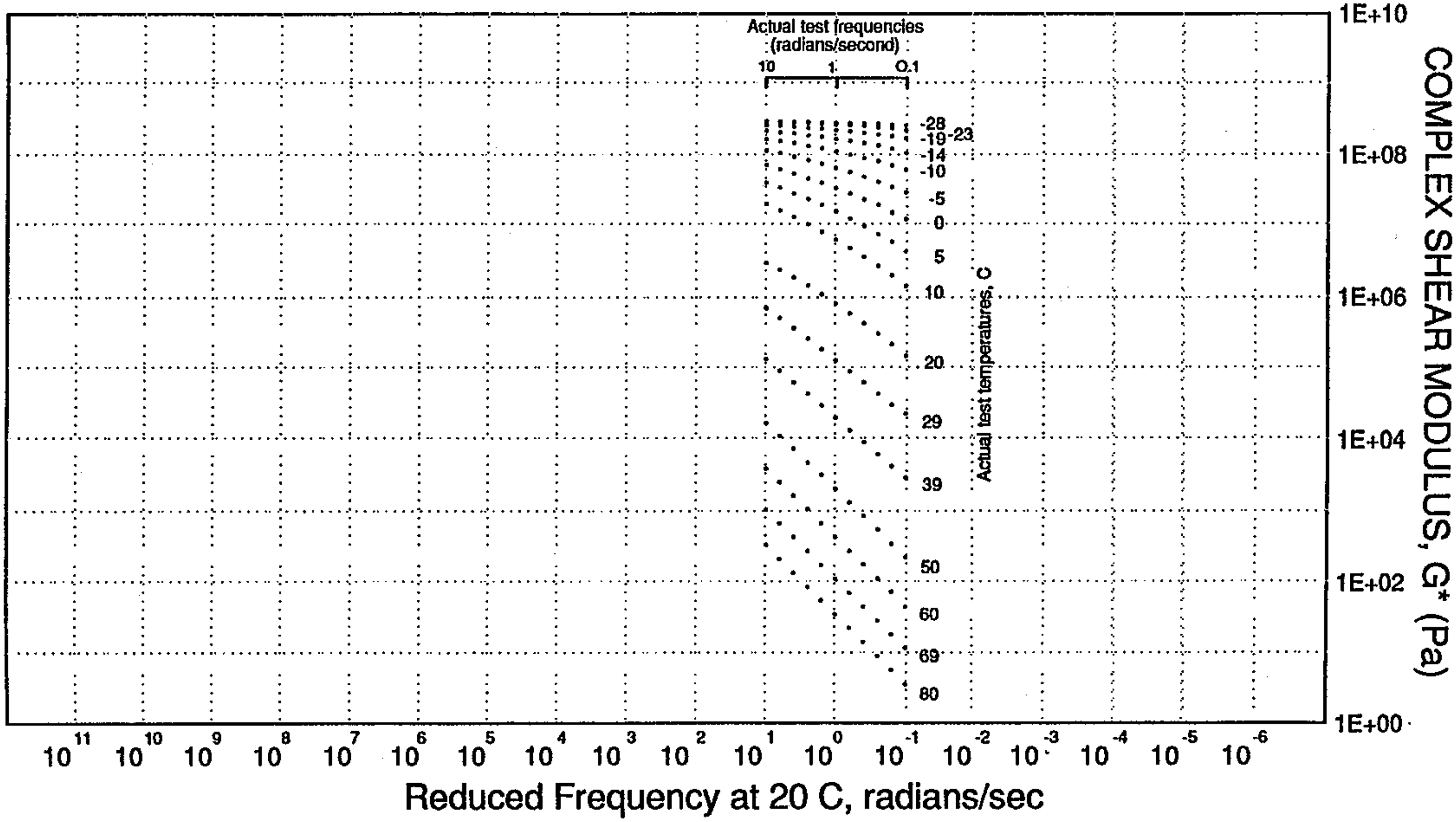
August 20, 1991

# FIGURE 5

## CREATING A MASTER CURVE FOR ASPHALT "D"




reference frequency: 10 radians/sec
reference temperature: 20 C

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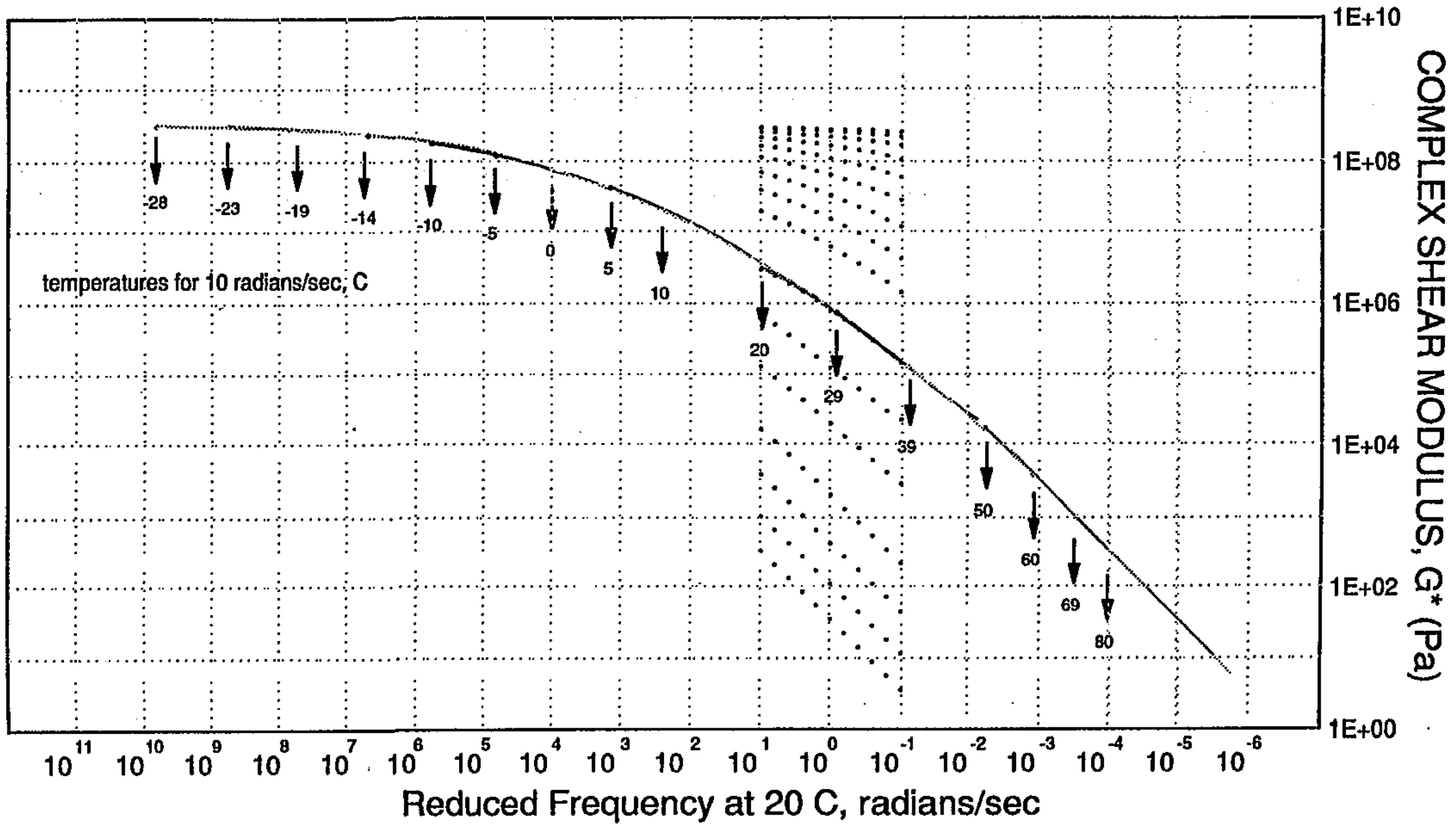
August 20, 1991

**FIGURE 6**

# CREATING A MASTER CURVE FOR ASPHALT "D"




reference frequency: 10 radians/sec
reference temperature: 20 C

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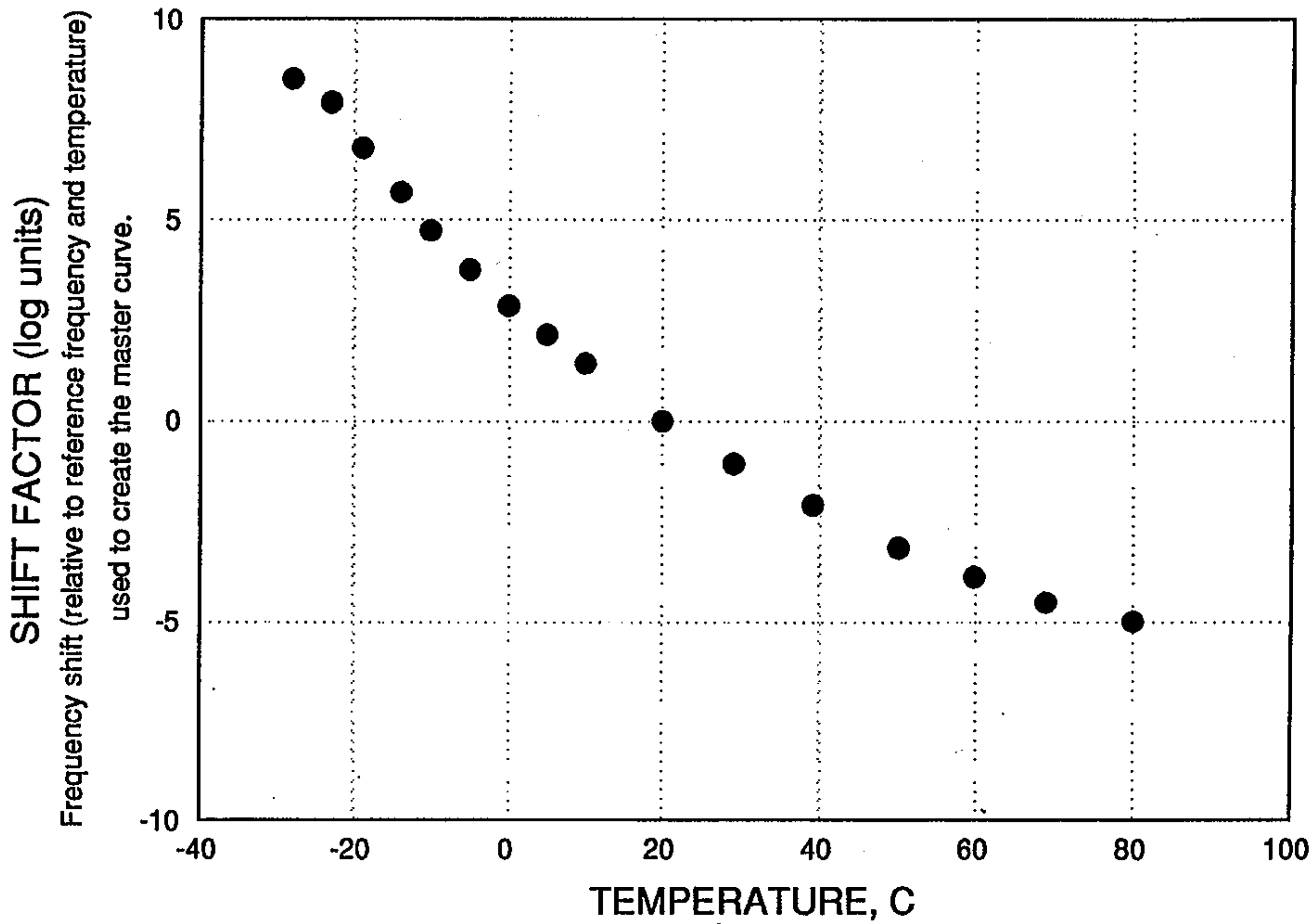
## FIGURE 7

## SHIFT FACTOR versus TEMPERATURE for ASPHALT "D"




reference frequency: 10 radians/sec
reference temperature: 20 C

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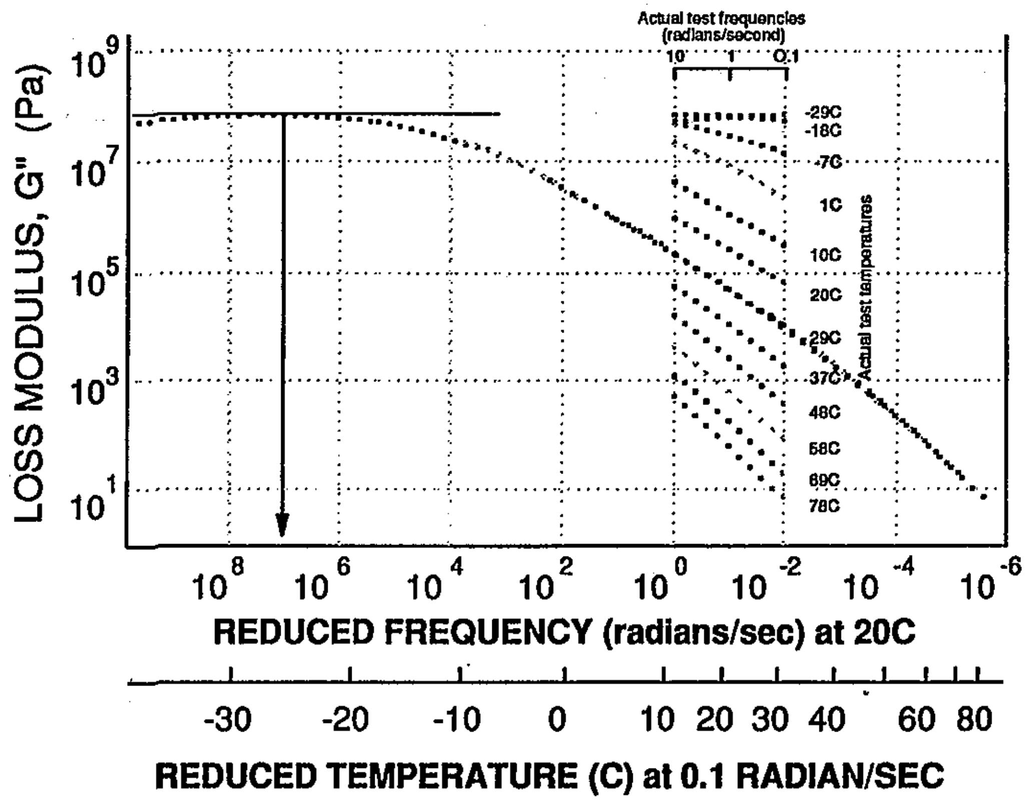
# FIGURE 8

## DYNAMIC MECHANICAL ANALYSIS
## TIME-TEMPERATURE SUPERPOSITION




Asphalt B

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